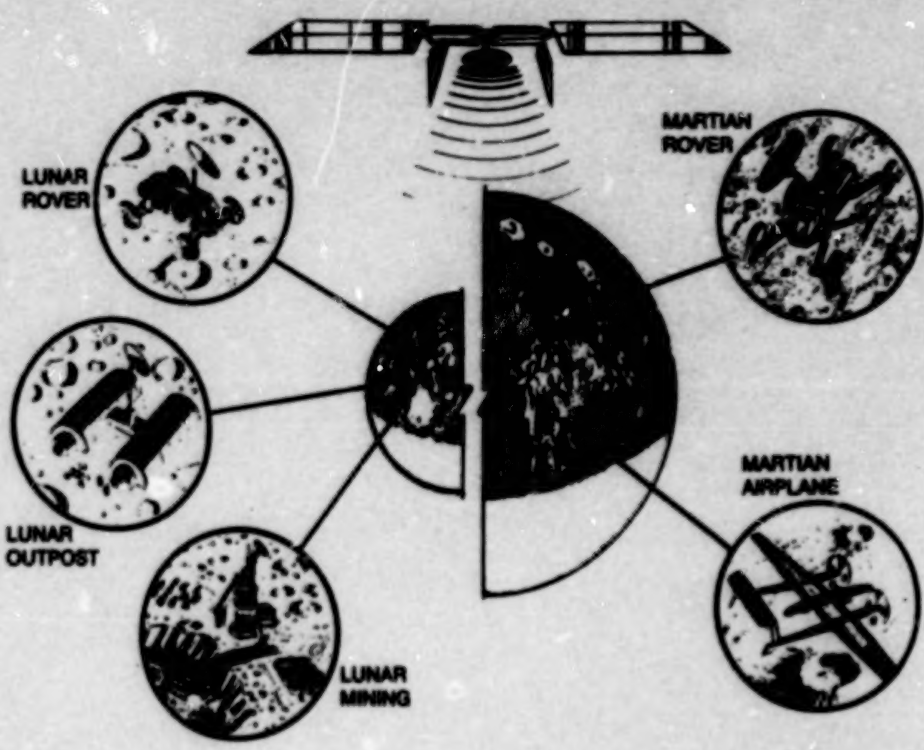
NASA Conference Publication 10016

Free-Space Power Transmission



Proceedings of a workshop held at NASA Lewis Research Center Cleveland, Ohio March 29–30, 1988

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Free-Space Power Transmission

Proceedings of a workshop sponsored by and held at
NASA Lewis Research Center
Cleveland, Ohio
March 29-30, 1988

NASA

National Aeronautics and
Space Administration

Scientific and Technical
Information Branch

1989

FOREWORD

NASA Lewis Research Center organized a workshop on technology applicable to free-space power transmission (beam power). This workshop took place March 29-30, 1988 at NASA Lewis Research Center.

The objective of the workshop was to create awareness of some of the technologies under development that might be applicable to the beam power concept.

To this end, invited speakers were asked to give an overview of their program, emphasizing

- Program objective
- Milestones
- Technology challenges
- Tradeoffs and payoffs
- Program cost

Speakers represented academia, industry, and our national laboratories currently engaged in developing microwave or laser technology for defense, NASA, or energy applications. Areas covered were rectenna technology; high-frequency, high-power generation (gyrotrons, solar-pumped lasers, and free-electron lasers); and antenna technology.

The guest speakers on rectenna technology were Raytheon Co., Georgia Institute of Technology, and the University of Cincinnati. The area of RF-laser technology was covered by Lawrence Livermore National Laboratories, the Department of Energy at Washington, D.C., the Naval Research Laboratories, the Massachusetts Institute of Technology, the University of Cincinnati, and NASA Langley Research Center. Finally, NASA Langley and L'Garde discussed antenna systems (structures and components).

The information presented can be used by the "beam power" community to assess the suitability of the different technologies to the free-space power transmission concept. Eventually, this assessment could help to outline a comprehensive program that would embrace technology development in the areas of antenna systems, RF-laser power generation, and rectenna systems.

It was not expected that at the conclusion of this workshop the participants would agree on the technology needed for free-space power transmission, nor was it expected that the deliberations at the end of the workshop would be able to outline what a comprehensive development program on beam power should be. It is more realistic to see this first workshop in this subject as a vehicle to establish communication between the beam power and RF-laser technology community and NASA.

The proceedings of the Workshop on Free-Space Power Transmission contain a collection of viewgraph presentations that describe the efforts by academia, industry, and our national laboratories in the area of high-frequency, high-power technology applicable to free-space power transmission systems.

It should not be thought that all the possible technologies to be considered for this application were represented in this workshop. On the contrary, the message of this workshop should encourage program managers of technologies not represented here to consider beam power as a possible application of their technology.

We would like to take this opportunity to thank all the invited speakers for their efforts, for their contributions, and for the volunteering of their time that culminated in the success of this workshop. Our deepest appreciation also is given to all the attendees for their presence and participation throughout all the discussions.

CONTENTS

PROGRAM BACKGROUND

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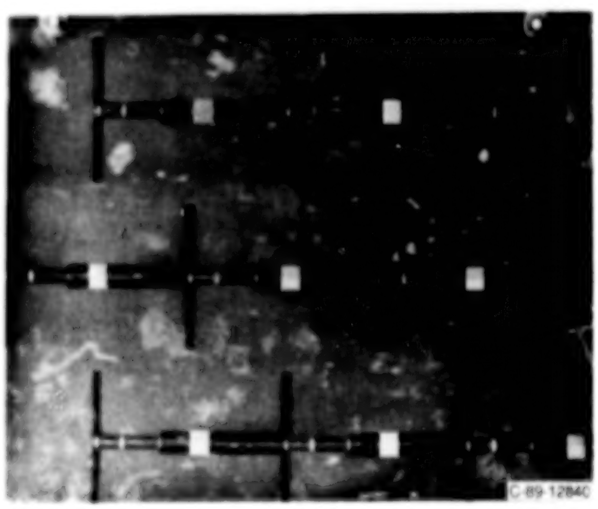
The concept of free-space power transmission has been around since the late 60's. During the early years of this technology several missions were depicted as possible beneficiaries of this concept. The one that received the most visibility was the Solar Power Satellite (SPS).

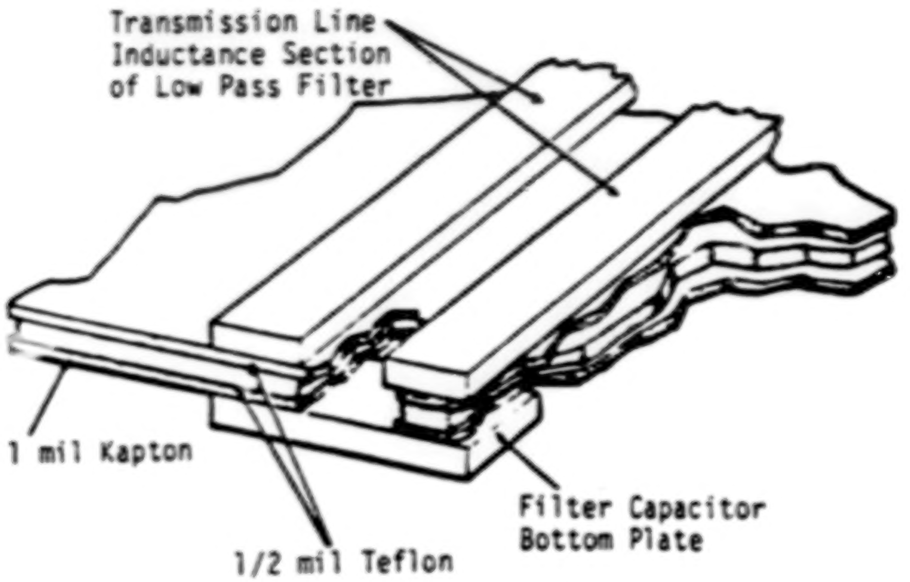
The SPS concept emerged in the midst of the energy crisis of the early 70's. A large amount of resources were invested by NASA and The Department of Energy in order to determine the feasibility and cost effectiveness of this system. Studies indicated that the SPS was technologically feasible. This was proven in part in 1975 when the first demonstration of this concept took place at the Goldstone Facility of the Jet Propulsion Lab. In this demonstration, 30 kW of cw power at 2.45 GHz was transmitted over a distance of 1.6 km.

Despite the technical feasibility of such a system, the initial investment to make the SPS system cost competitive was higher than what the U.S. utility industry was willing to make in such a high risk enterprise. The momentum generated by the SPS concept during the early 70's quickly diminished when the energy crisis ended almost a decade later.

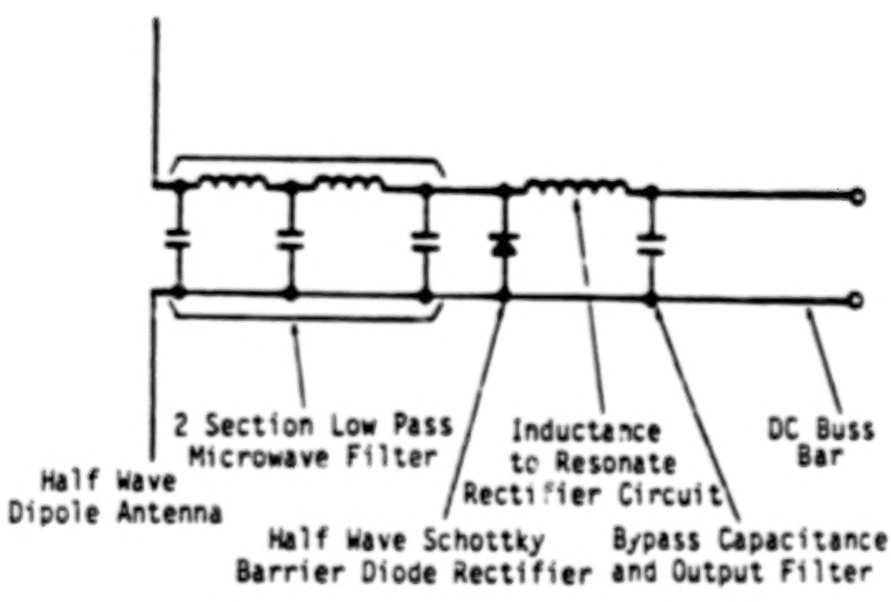
The experience gained during the SPS era gave way to other applications for the free-space power transmission concept. Two examples are a LEO to GEO transport utilizing a combination of beam power and electric propulsion systems (NASA contract NAS3-25066) and the CO-OPS (Carbon Dioxide Observational Platform System) (NASA TP-2696). The primitive bar-type rectenna, previously developed for the SPS, was modified for these kinds of aerospace applications (NAS3-22764). The newly redesigned rectenna was built on a thin-film mylar substrate yielding 200 g/m^2, 1 kW/m^2, and about 85 percent efficiency at 2.45 GHz.



2.45-GHz THIN FILM RECTENNA. DESIGNED BY RAYTHEON UNDER NASA CONTRACT NAS3-22764.

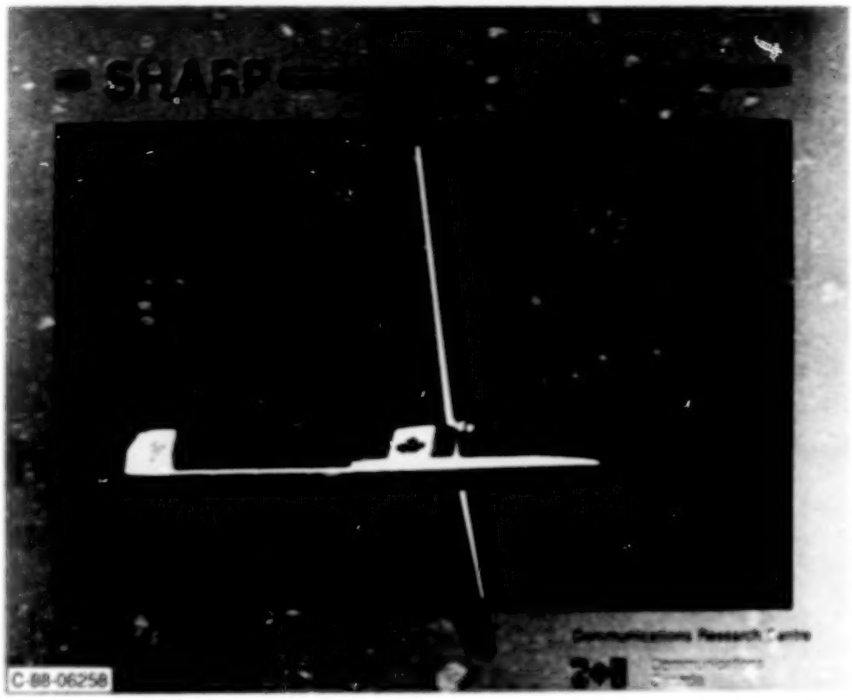


2.45-GHz THIN FILM RECTENNA SCHEMATIC.

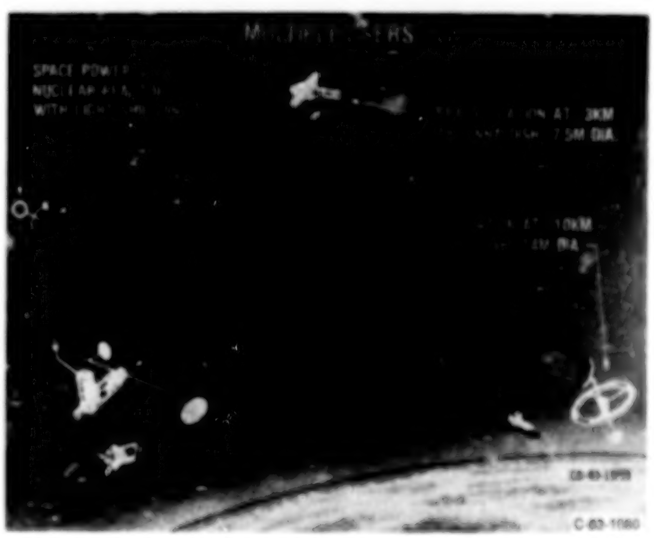


2.45-GHz THIN FILM RECTENNA RLC CIRCUIT EQUIVALENT.

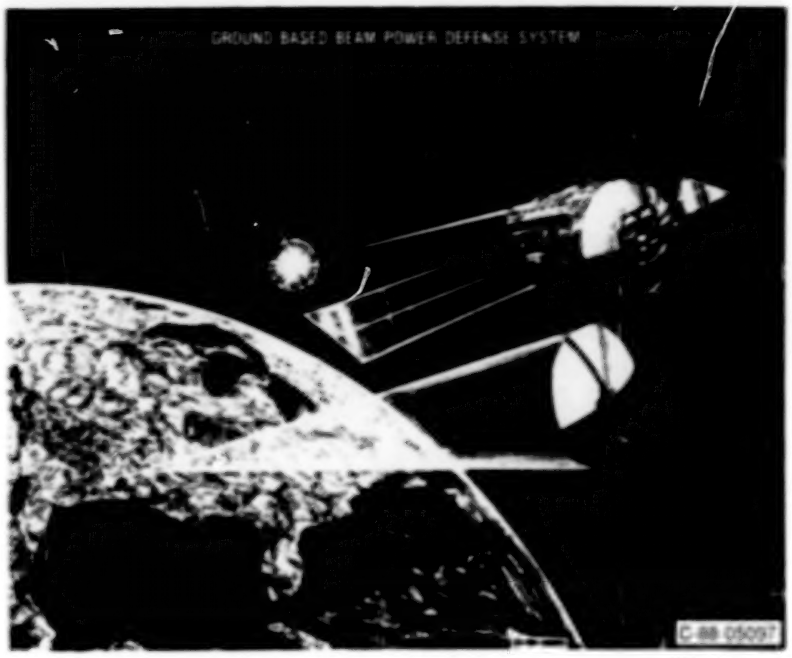
The first prototype vehicle to use this kind of rectenna was the Canadian version of the CO-OPS program called SHARP (Stationary High Altitude Relay Platform). The SHARP prototype vehicle was a 4.5-m wingspan, 4.1-kg (1-kg payload) aircraft that flew at an altitude of 150 m and was powered by a 150-W electric engine. This program is sponsored by the Canadian Communications Research Centre. The objective of this program, as in the case of the CO-OPS program, is to provide a "poor man's satellite" system suitable for tasks such as communication relay, surveillance, and air traffic control. This drone would be a retrievable aircraft, capable of flying unrefueled at an altitude of 21 km while carrying a payload of about 100 kg, and would be completely powered by microwaves from the ground. Such a system could cover a range of about 500 km (or about 780 000 km^2) at a fraction of the cost of a communication satellite or an AWACS airplane.



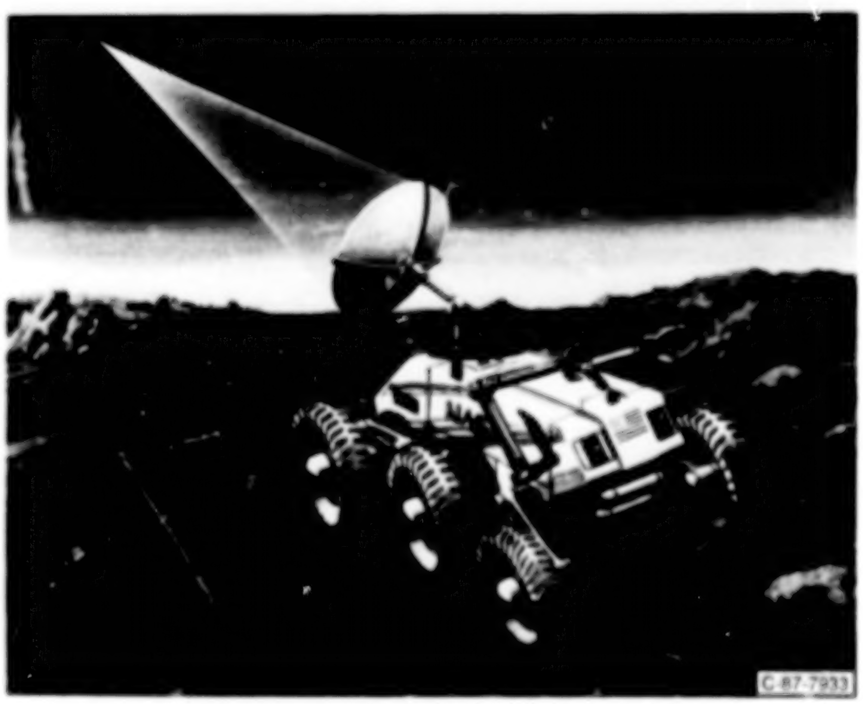
For space applications, the concept of free-space power transmission is also very attractive. It would allow the power plant and energy storage to be located away from the space vehicle or platform, thus drastically reducing the spacecraft mass. This mass reduction in the vehicle could reduce the launch cost and enhance maneuverability of the vehicle.



In near-Earth space we could imagine a constellation of free flyers being fed by a coorbiting central multimegawatt nuclear station. In other more advanced cases we could imagine a central station located at geosynchronous orbit (GEO) supplying power to several users between low Earth orbit (LEO) and GEO. Linking a multiplicity of space activities such as transportation, space stations, industrial, and military platforms to a single power station, the user is free to design his system according to his power demands, unconstrained by power availability. This scenario is analogous to that of Earth where homes, industries, and ground transportation are linked by central power utility industries.

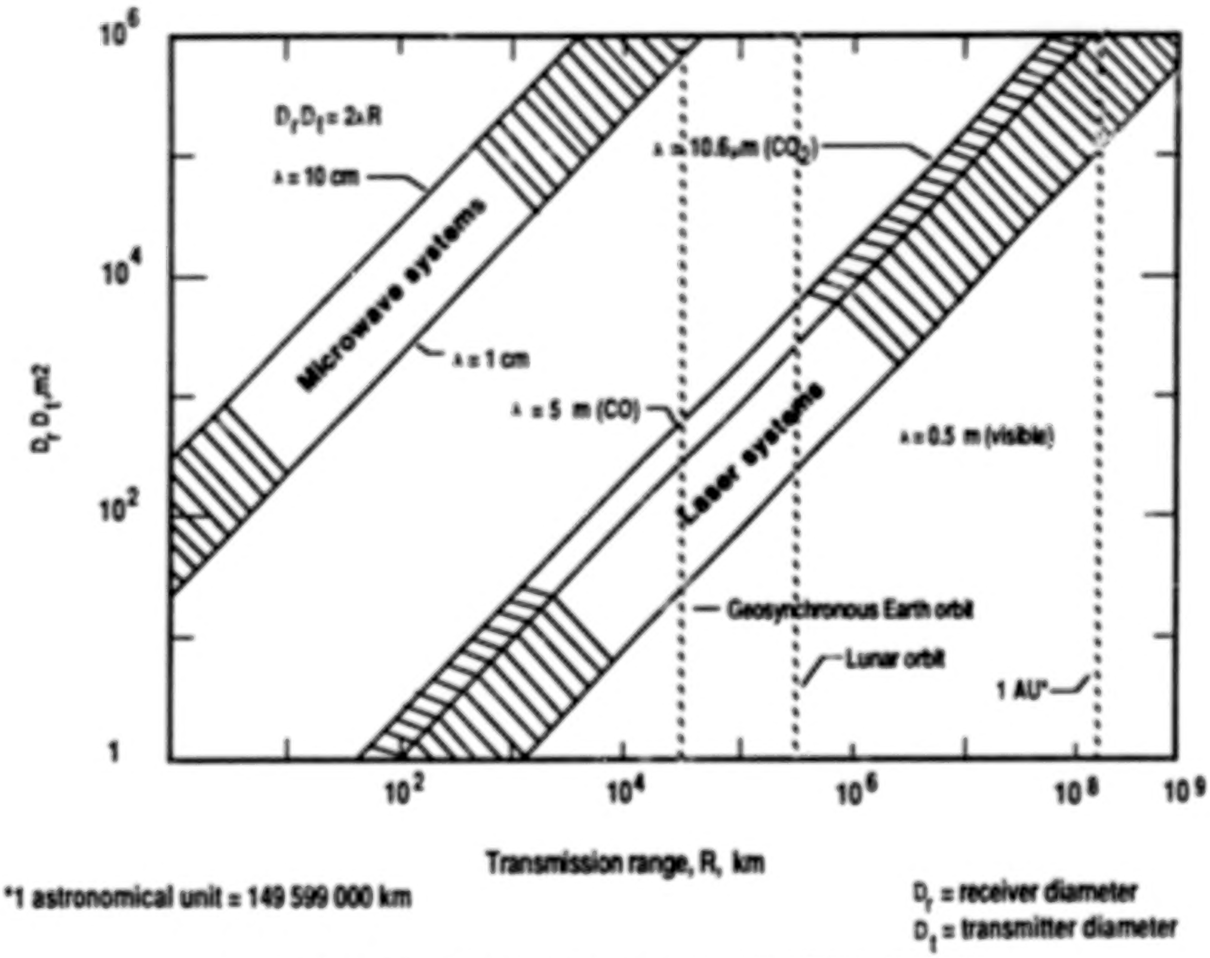


This concept of space-based utility power stations could be also extrapolated to planetary exploration and colonization. In most space exploration scenarios, large cargo vehicles utilizing electric propulsion systems powered by multimegawatt nuclear reactors have been envisioned. Once the vehicle has completed its mission of transporting cargo between Earth and its destination, the vehicle could be placed at a specific orbit and then beam the power down to the surface. This could provide sufficient surface power for manned bases and also to surface transport systems (rovers), without having to land the reactor on the surface or, for manned missions, to add extra shielding.



MOTHER SHIP ON MARS SYNCHRONOUS ORBIT. BEAMING POWER DOWN TO SURFACE TO ROVER.

In all these missions, the distance that would separate the receiver and the transmitter could range from several hundred to several thousand kilometers. Parametric analysis should be made to investigate the tradeoffs between antenna sizes, operating frequency, and range of the mission, taking into consideration the technology difficulties encountered in RF components at high frequency. Preliminary results indicate that for most of the missions described above, by operating at frequencies at the millimeter wavelength level or higher, antenna dimensions could be kept at a reasonable size.



TRANSMITTER AND RECEIVER SIZES AS A FUNCTION OF SEPARATION DISTANCE; NASA SP-464.

More research and development in areas of antenna systems, RF power generation and rectenna technology is necessary in order to have a working system operating at these frequencies. A substantial effort in these areas is being sponsored by the government, the military, academia, and industry. Although not all this effort is directed toward the development of a free-space power transmission system, the outcome of these programs should be applicable to beam power technology.

NASA Lewis Research Center has sponsored a 3-year effort to develop high-frequency rectennas. Two frequencies were chosen for development: 300 GHz by the Georgia Institute of Technology (NASA Grant NAG3-282) and 28 THz (far-infrared) by the University of Cincinnati (NASA Grant NAG3-532). At the termination of both grants, some encouraging results were obtained, although no operational devices were completed.

Work on large deployable antenna systems in space has been largely funded by NASA Langley Research Center. Among these systems, the most applicable for beam power appears to be inflatable antennas. This effort was performed under contract by L'Garde INC., at Newport Beach, California (NASA Contract NAS1-16663). This same concept was proposed for light-weight solar concentrators in space at Edwards Air Force Base. This research study was contracted to Spectra Research Systems (AFRPL-TR-84-040) and L'Garde INC. (AFRPL-TR-84-021) by the Airforce Rocket Propulsion Laboratory at Edwards AFB.

Finally, the Department of Defense and the Department of Energy have embraced a comprehensive program to develop high-frequency, high-power sources. Among these sources are the gyrotron and the free-electron laser. The major application of these types of sources is for plasma heating (in the case of fusion energy research) and weapon systems.

The following viewgraph presentations describe the effort by academia, industry, and our national laboratories in the area of high-frequency technology applicable to free-space power transmission systems. The areas covered are rectenna technology, high-frequency, high-power generation (gyrotrons and free-electron lasers), and antenna technology.

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AN ALL ELECTRONIC TRANSPORTATION SYSTEM FROM LEO TO GEO AND BEYOND

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Waltham, Massachusetts 02254

System description and moon mission interface. The all electronic LEO to GEO transportation system (1) now being studied by NASA as part of the space transportation infrastructure and that combines the high specific impulse of the ion thruster with beamed microwave power may have application to a moon or Mars mission. The range of the system can probably be extended to twice GEO distance where 80% of the delta V required for the moon mission will have occurred. In principle the electronic OTV (orbital transfer vehicle) transports the moon mission to twice GEO, comes back to perform its routine LEO to GEO function, and then later retrieves the mission when it returns from the moon. The system schematic and a diagram of the complete, four beam system are shown in Figure 1. All elements of the system must be located in the equatorial plane to allow beam contact with the OTV each time it orbits the earth. This location is consistent with minimum launch costs to LEO and GEO and a joint use of the ground-based installation to beam low cost power to "orbiting industrial parks".

LEO to GEO flight times. The low combined mass of the ion thruster and the microwave receiver relative to the thrust generated allows large, unanticipated accelerations of an electric OTV. LEO to GEO flight times of about 10 days can be projected for an express (small payload) mission, after making allowances for initial intermittent contact with the microwave beam. Figure 2 shows the transport times for single and four beam systems for a 51% payload.(2)

Technology readiness and modular construction. The technologies of both the space portion (ion thrusters and "rectenna") are well developed but their interfacing needs experimental study. Modular construction allows easy expansion of both space and ground systems. Many low-cost microwave components are available.

System capacity and costs. A full scale system (4 beams and 4 OTVs) could handle up to 60,000,000 kg/yr of payload to GEO. Costs for 60 cycle earth power and 10 yr. system amortization cost, on basis of $/kg of payload, are each estimated to be $15/kg for a full scale system. Smaller systems will cost more but are still very attractive.

Reduction of propellant mass. The amount of ion thruster propellant needed in LEO for a typical round trip to GEO with payload is typically less than 10% that of propellant for conventional chemical rockets. Argon or xenon may be used.

(1) W. C. Brown. AIAA-85-2045 paper. Int'l Electric Propulsion Conf. Oct. 1985
(2) W. C. Brown. Science Technology Series, Vol 67, 1987 Amer. Astro. Soc.

Abstract for the Symposium
Lunar Bases and Space Activities of the 21st Century
Houston, Texas April 5 - 7 1988

UNIQUE PROPERTIES OF MICROWAVE POWER TRANSMISSION TO TRANSFER ENERGY

- NO MASS REQUIRED BETWEEN SOURCE OF ENERGY AND POINT OF CONSUMPTION

  NO WIRES
  NO FERRYING VEHICLES

- ENERGY CAN BE TRANSFERRED AT VELOCITY OF LIGHT

- DIRECTION OF ENERGY TRANSFER CAN BE RAPIDLY CHANGED

CHARACTERISTICS COMMON TO ALL APPLICATIONS

EQUATORIAL PLANE
  BOTH UPLINK APPLICATIONS COMPLETELY IN PLANE
  DOWNLINK TRANSMITTER IN PLANE

FREQUENCY --- 2.45 GIGAHERTZ (12 CM) OR CLOSE TO IT

ELECTRONICALLY STEERABLE PHASED ARRAY TRANSMITTERS
  COMPOSED OF MODULES

DEVICE THAT SIMULTANEOUSLY ABSORBS MICROWAVE POWER
  AND RECTIFIES IT TO DC POWER AT 80+% EFFICIENCY

LARGE AND VERY HIGH POWER SYSTEMS

ORIGINAL PAGE IS
OF POOR QUALITY

UNIQUE PROPERTIES OF MICROWAVE POWER TRANSMISSION TO TRANSFER ENERGY

- NO LOSS OF ENERGY TRANSFER IN VACUUM OF SPACE LITTLE LOSS IN EARTH'S ATMOSPHERE AT THE LONGER MICROWAVE WAVELENGTHS
- THE MASS OF THE POWER CONVERTERS AT THE TERMINALS CAN BE SMALL
- ENERGY TRANSFER BETWEEN POINTS IS INDEPENDENT OF GRAVITATIONAL POTENTIAL

BEAMED MICROWAVE POWER TRANSMISSION SYSTEM

DC TO MICROWAVE CONVERSION	BEAM FORMING ANTENNA	FREE SPACE TRANSMISSION	RECEPTION CONVERSION TO DC
70 - 90 %	70 - 97 %	5 - 95 %	85 - 92%

MAXIMUM POSSIBLE DC TO DC EFFICIENCY --- 76%

EXPERIMENTAL DC TO DC EFFICIENCY --- 54%

SOLAR POWER SATELLITE EFFICIENCY --- 58-72%

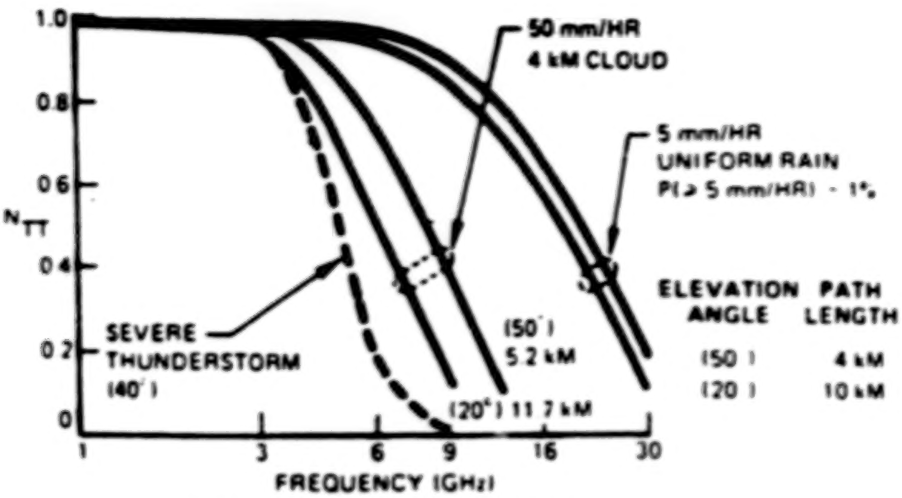
BEAMED MICROWAVE POWER TRANSMISSION SYSTEMS INTERRCONNECTING EARTH AND SPACE

UPLINKS

- o ALL ELECTRONIC TRANSPORTATION SYSTEM FROM LOW EARTH ORBIT TO GEOSYNCHRONOUS ORBIT
- o ELECTRIC POWER BEAMED TO "ORBITING INDUSTRIAL PARKS"

DOWNLINK

- o TRANSFER OF POWER DERIVED FROM THE SUN IN GEOSYNCHRONOUS ORBIT TO THE EARTH.- THE SOLAR POWER SATELLITE CONCEPT



TRANSMISSION EFFICIENCY
MOLECULAR ABSORPTION AND RAIN

FOCUS ON ALL ELECTRONIC TRANSPORATION SYSTEM FROM LEO TO GEO

- o SAFE, RELIABLE, AND "LOW G"
  BUT, SHORT, UNANTICIPATED TRANSPORT TIMES FOR AN ELECTRIC PROPELLED VEHICLE
- o LOW COST IN COMPARISON WITH OTHER TECHNOLOGIES
- o MODULAR APPROACH ALLOWS EASY EXPANSION OF MICROWAVE SYSTEM AND TRANSPORT TONNAGE
- o COMPONENTS OF SYSTEM IN ADVANCED STATE OF DEVELOPMENT

HYPOTHETICAL MISSION TO MARS
100,000 KG FROM GEO TO MARS; 25,000 KG FROM MARS TO LEO

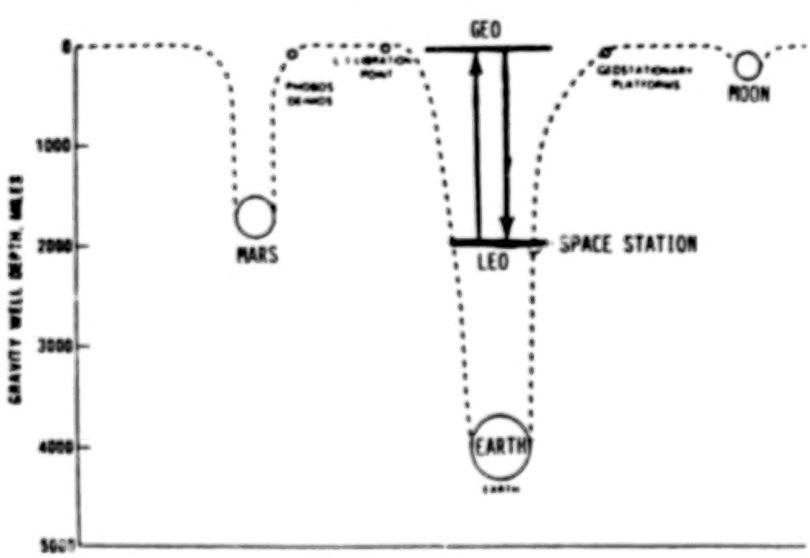
	Chemical Rockets	Ion Thrusters
Mass of Propellant From Earth to LEO for OTV*	1,150,000 KG	27,500 KG
No. of Shuttle Payloads at 30,000 KG	38	1
Cost of Transportation at $2,000/KG	$2,300,000,000	$55,000,000

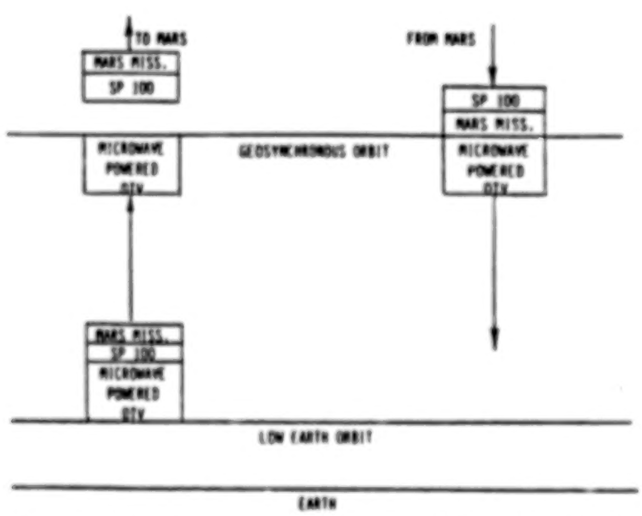
* OTV transports 100,000 kg to GEO and then later picks up 25,000 kg return mission at GEO and returns to LEO.

LARGE AND VERY HIGH POWER SYSTEMS

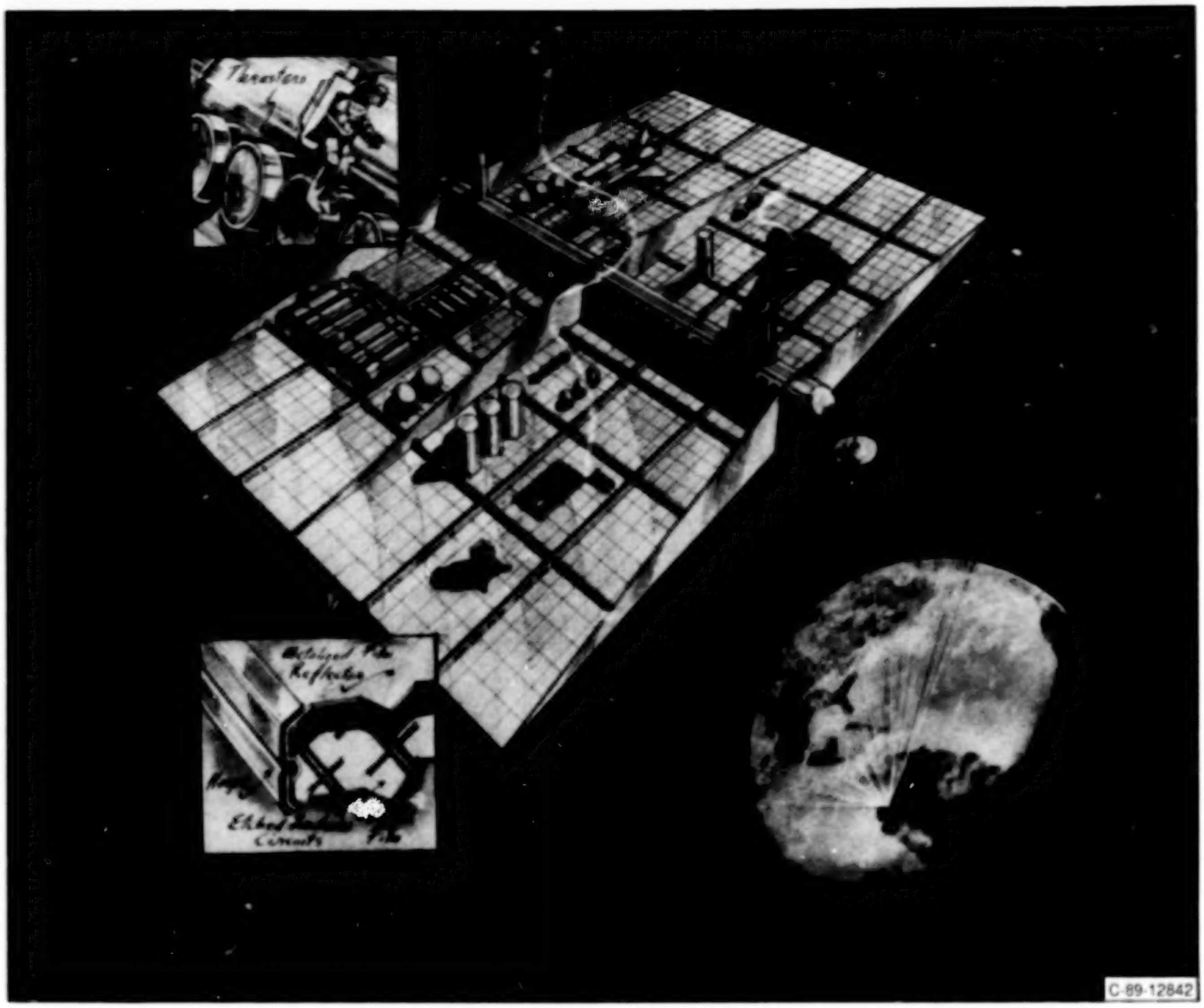
APPLICATION	TRANSMISSION DISTANCE KILOMETERS	APERTURE RADIUS METERS	POWER MEGAWATTS
SOLAR POWER SATELLITE	36.000	1280	6000
LEO TO GEO ORBITAL TRANSFER VEHICLE	36.000	750	400
ORBITING INDUSTRIAL PARK	400	124	20
STRATOSPHERIC AIRCRAFT PLATFORM	20	28	1

INNER SOLAR SYSTEM GRAVITY WELLS





A HYPOTHETICAL MARS MISSION WITH HYBRID POWER SOURCES FOR ELECTRIC PROPULSION



PHYSICAL SHAPE AND ORBITAL ATTITUDE OF ORBITAL TRANSFER VEHICLE

- o IN APPEARANCE THEY ARE LARGE, PLANAR , MONOLITHIC STRUCTURES
- o RECTENNA IS LARGE IN AREA TO (1) SUPPLY LARGE AMOUNTS OF POWER NEEDED FOR PROPULSION, AND (2) TO INTERACT EFFICIENTLY WITH MICROWAVE BEAM
- o IN ATTITUDE, THE FLAT FACE OF THE VEHICLE ALWAYS REMAINS PARALLEL TO THE EARTH'S SURFACE.

THE SYSTEM IS BASED IN THE EQUATORIAL PLANE

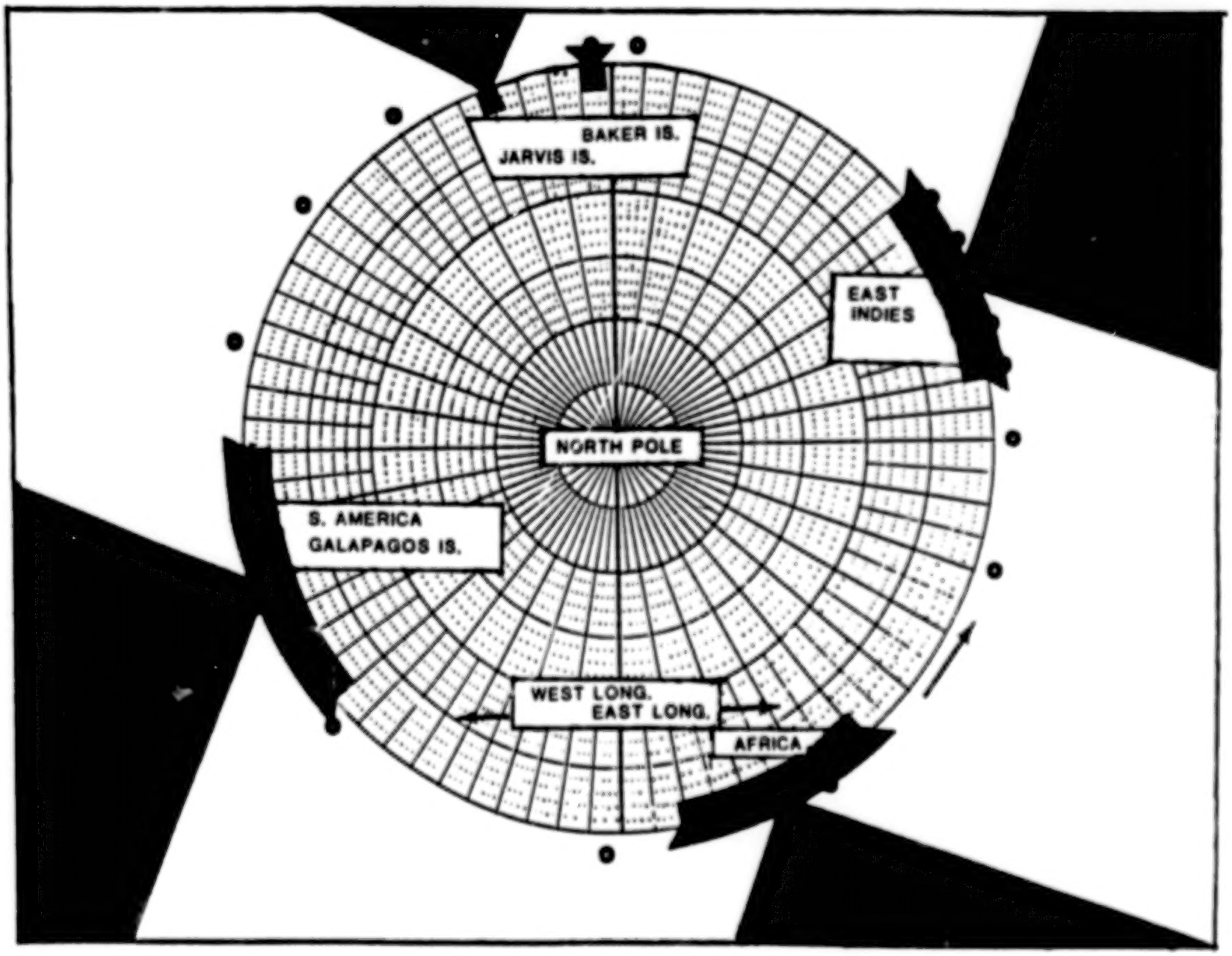
<u>WHY?</u>

- ONLY IN THE EQUATORIAL PLANE DO THE SATELLITES PASS OVER THE MICROWAVE TRANSMITTERS EACH TIME THEY ENCIRCLE THE EARTH.
- COST OF TRANSMITTERS TO SWING BEAM THROUGH ONE PLANE ONLY IS SMALL FRACTION OF COST OF TRANSMITTERS THAT HAVE NO SUCH RESTERICTION.

<u>IMPLICATIONS OF THE EQUATORIAL PLANE</u>

- THE FULLY OPERATIONAL SYSTEM IS INTERNATIONAL IN CHARACTER
- SYSTEM IS CONSISTENT WITH LOWER LAUNCH COSTS AT THE EQUATOR
- THERE ARE ENOUGH LAND SITES TO PROVIDE A 25% DUTY CYCLE IN LOW LEO
- THERE ARE ENOUGH LAND SITES TO LOCATE FOUR LARGE TRANSMITTERS TO PROVE 100% DUTY CYCLE FOR ORBITS 10.000 KM ABOVE EARTH'S SURFACE
- SYSTEM CAN SUPPLY PRIME OR AUXILLIARY POWER TO "<u>ORBITING INDUSTRIAL PARKS</u>"* IN LOW EARTH ORBIT.

*PAGE 20-REPORT OF THE NAT'L COMMISSION ON SPACE



LAND MASS AVAILABILITY FOR MICROWAVE TRANSMITTERS

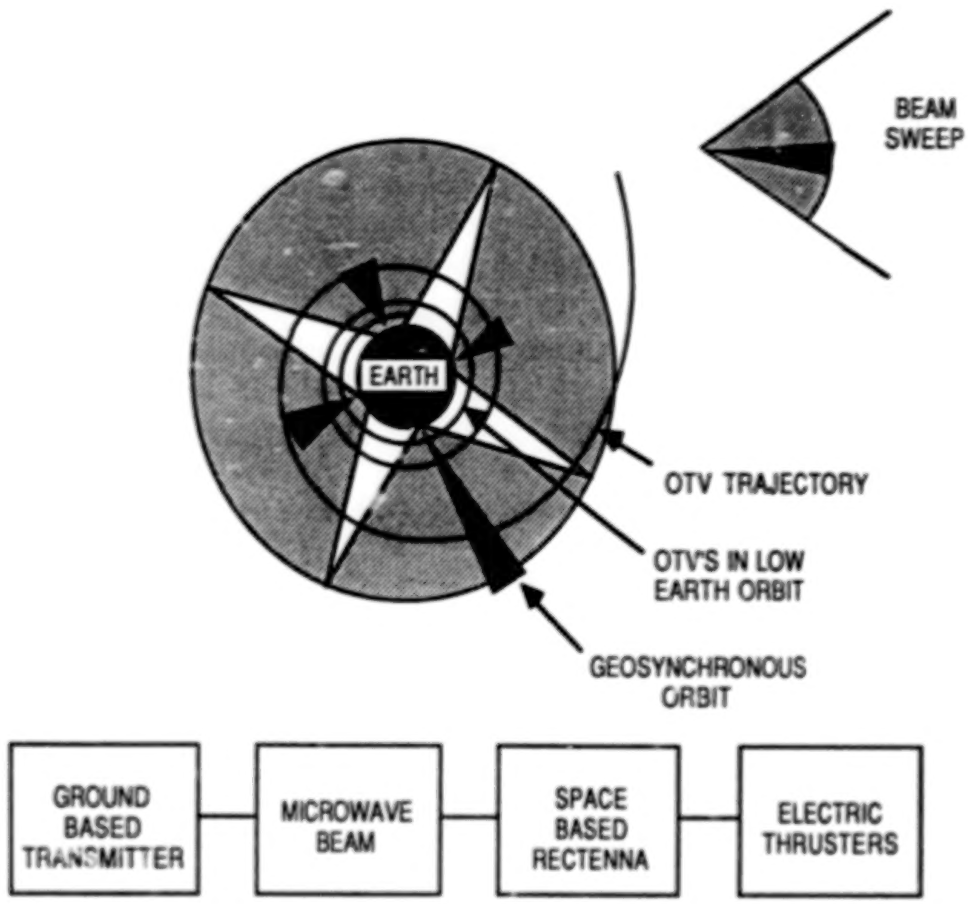
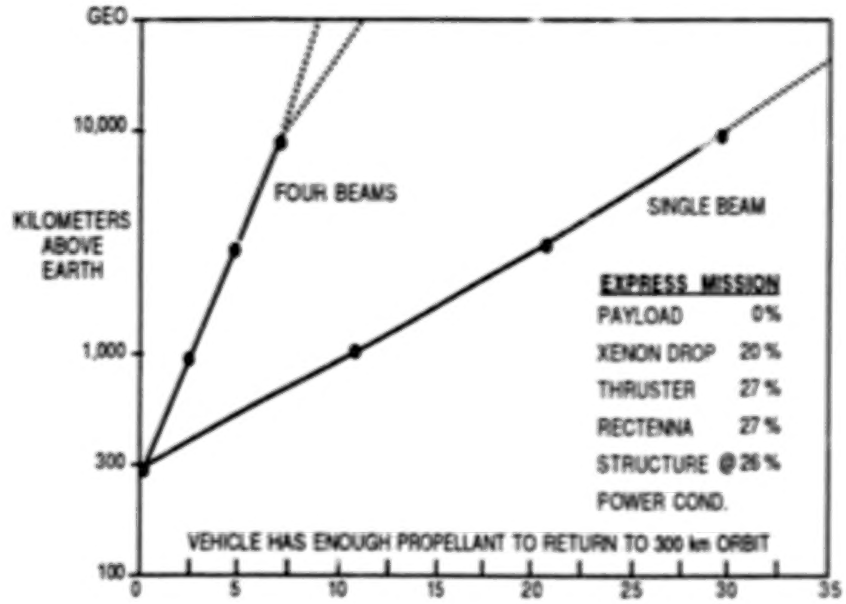


Fig. 1. LEO to GEO Electronic Transportation System

FIGURE ABOVE SHOWS ESSENTIAL FEATURES OF LEO TO GEO TRANSPORTATION SYSTEM. THE TRAJECTORY OF THE ORBITAL TRANSFER VEHICLE IS A SPIRAL. AN ELECTRONICALLY SWEPT MICROWAVE BEAM ENGAGES THE SATELLITE AS IT PASSES OVER THE TRANSMITTER. THE ENGAGEMENT TIME IS SHORT IN LEO BUT RAPIDLY INCREASES AS THE OTV GAINS ALTITUDE. THE FULLY DEPLOYED SYSTEM WOULD USE FOUR TRANSMITTERS SPACED ABOUT EQUALLY AROUND THE EARTH.

THE MICROWAVE BEAM POWERED ELECTRIC TRANSPORTATION SYSTEM FROM LEO TO GEO CONSISTS OF AN ELECTRONICALLY STEERED MICROWAVE BEAM ORIGINATING AT THE EARTH'S SURFACE THAT AUTOMATICALLY TRACKS THE ORBITAL TRANSFER VEHICLE THAT IS EQUIPPED WITH A RECTENNA TO CAPTURE THE MICROWAVE BEAM AND TO CONVERT IT INTO DC POWER FOR THE ELECTRIC THRUSTERS.



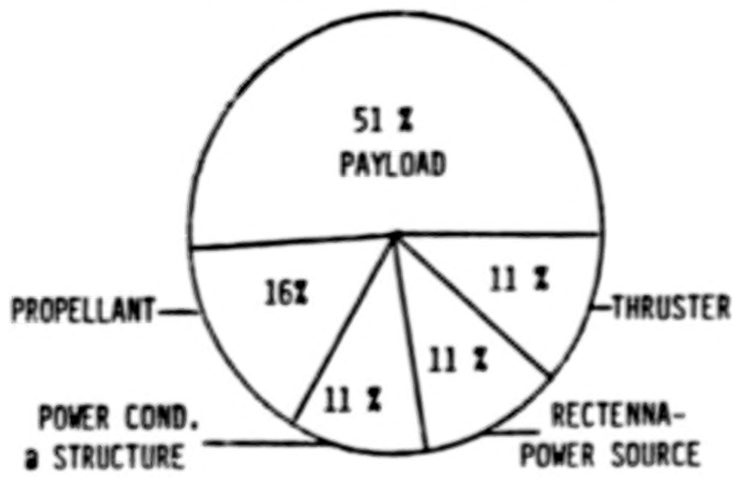
DAYS OF TOTAL ELAPSED TIME AFTER START AT 300 KILOMETER ORBIT

FEATURES OF ALL ELECTRONIC LEO TO GEO TRANSPORTATION SYSTEM

- MASSES OF ION THRUSTER AND RECTENNA ARE BOTH A LOW 1 kg/kW (OR LESS) MAKING POSSIBLE EXPRESS MISSIONS TO GEO OF TWO WEEKS OR LESS
- VEHICLE CAN START AT 300 KILOMETER ORBIT
- COMPLEXITY AND COST OF POWER CONDITIONING ARE LOW
- RECTENNA AS POWER SOURCE HAS MANY GOOD FEATURES:
  - IT IS IN AN ADVANCED STATE OF DEVELOPMENT
  - SIMPLE TO MANUFACTURE WITH EXISTING FACILITIES
  - NO AUXILIARY COOLING NECESSARY
  - POTENTIAL FOR VERY LONG LIFE (DECADES)
  - HIGHLY RELIABLE BECAUSE OF SIMPLICITY
  - AREA AND POWER EXPANSION EASY (MODULARITY)
  - NO IONIZING RADIATION
  - MODULES CAN BE CONNECTED IN SERIES OR PARALLEL TO MATCH COMPONENT REQUIREMENTS

MICROWAVE BEAM POWERED MISSION

TNTTIAL ACCELERATION - 0.006 M/S



BREAKDOWN OF SPACECRAFT MASSES FOR XE: I_{SP} OF 4200
INITIAL CONDITION: 300 KILOMETER CIRCULAR ORBIT
MISSION: OTV DELIVERS PAYLOAD TO GEO AND RETURNS TO LEO

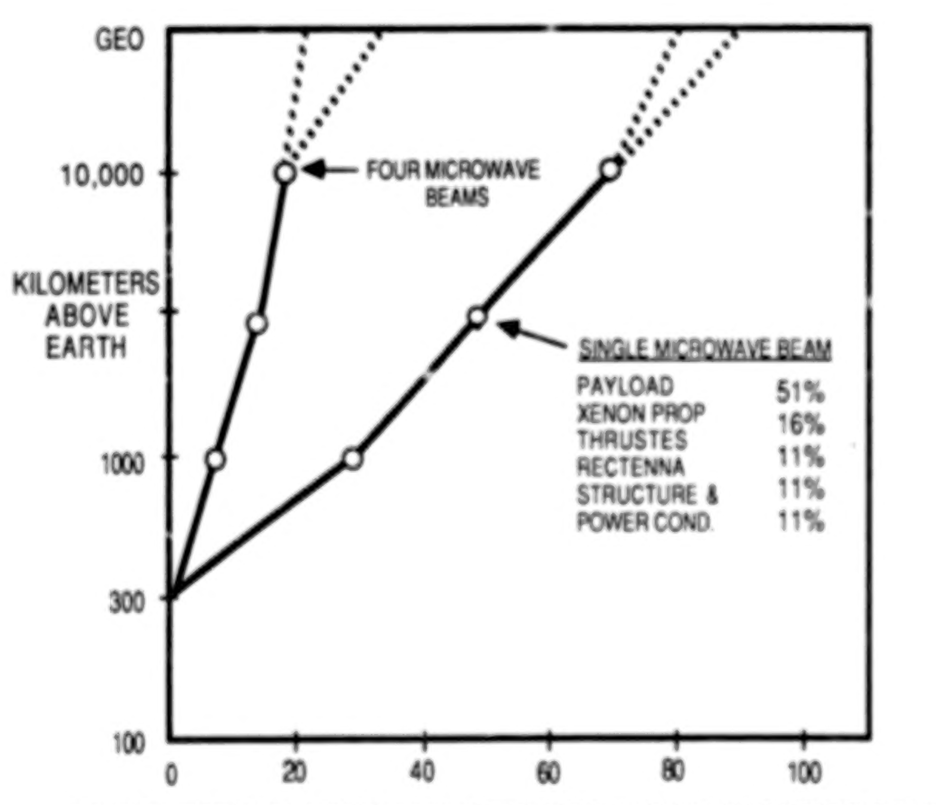
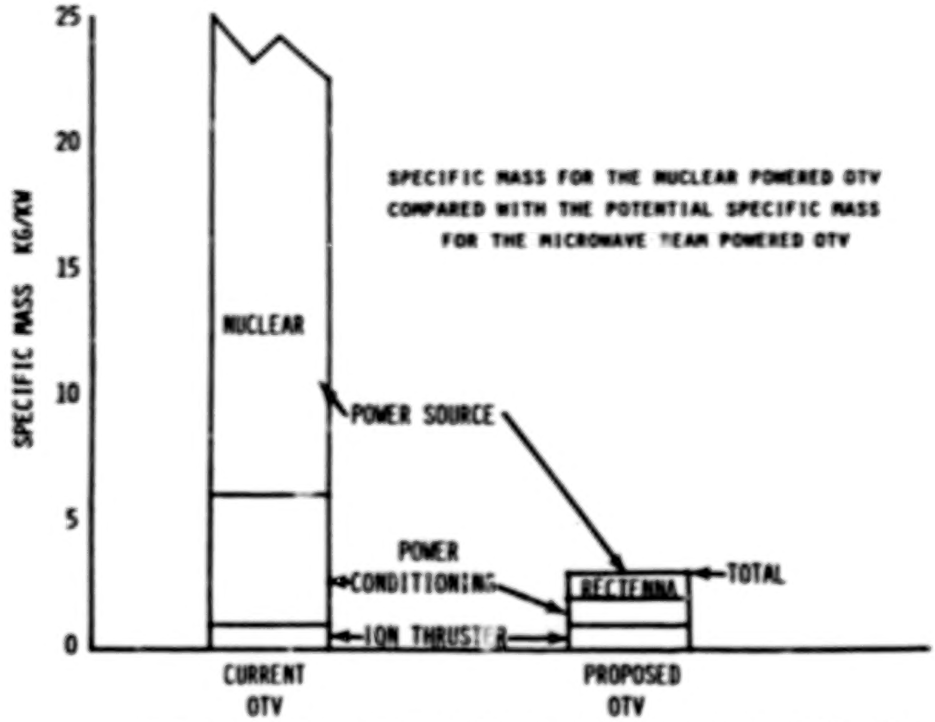
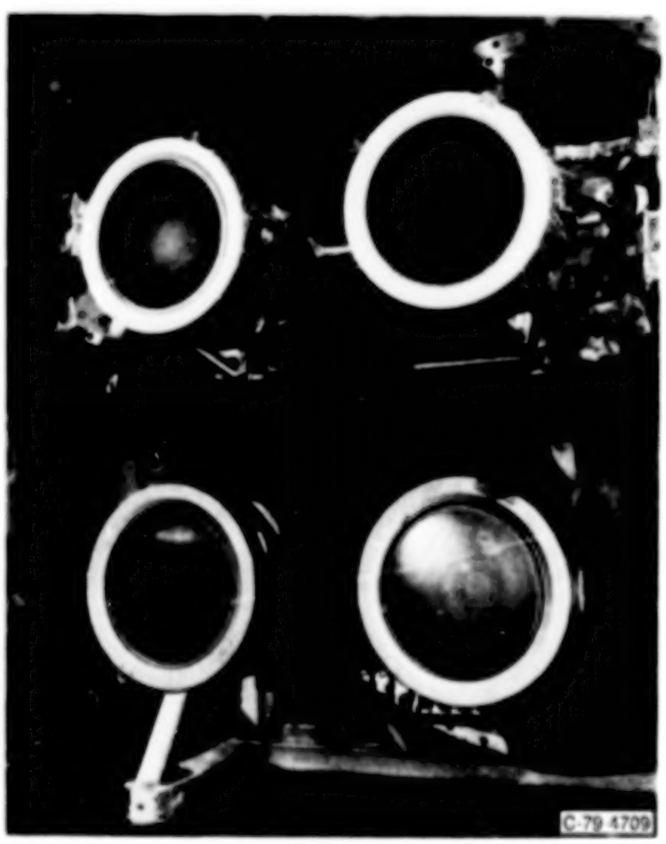


FIG. 2. Orbit Altitude as a Function of Elapsed Time



THE SPECIFIC MASS OF THE DRY VEHICLE CAN POTENTIALLY BE REDUCED BY A FACTOR OF 10 BY THE MICROWAVE BEAMED POWER SOURCE. THIS REPRESENTS A MAJOR PERTURBATION IN THE APPLICATION OF ELECTRIC PROPULSION.



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MILLIMETER WAVELENGTH RECTENNA DEVELOPMENT

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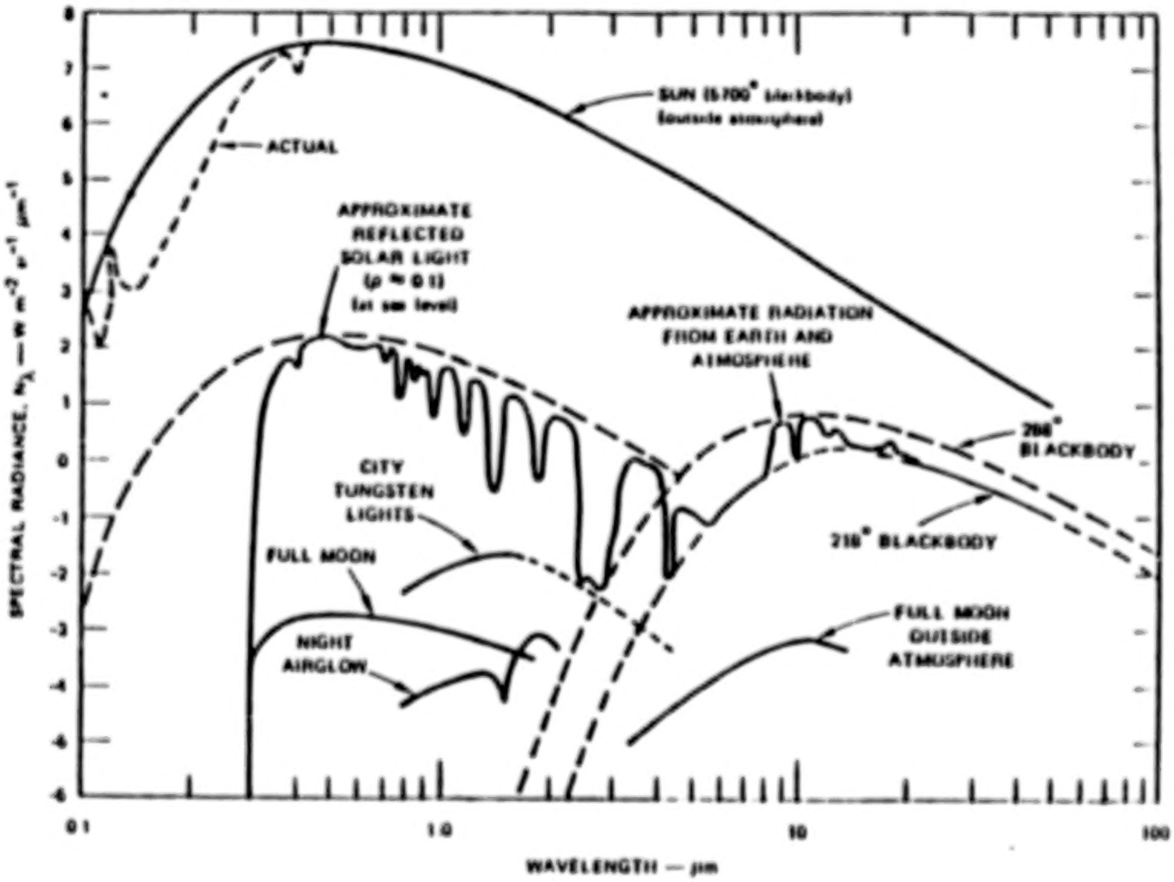
GEORGIA TECH STARTED STUDYING RECTENNAS WITH THE INTENT OF CONVERTING THE EARTH'S (BLACK BODY) RADIATION IN TO DC POWER FOR SATELLITES IN EARTH ORBIT.



SPECTRAL RADIANCE OF SUN AND EARTH

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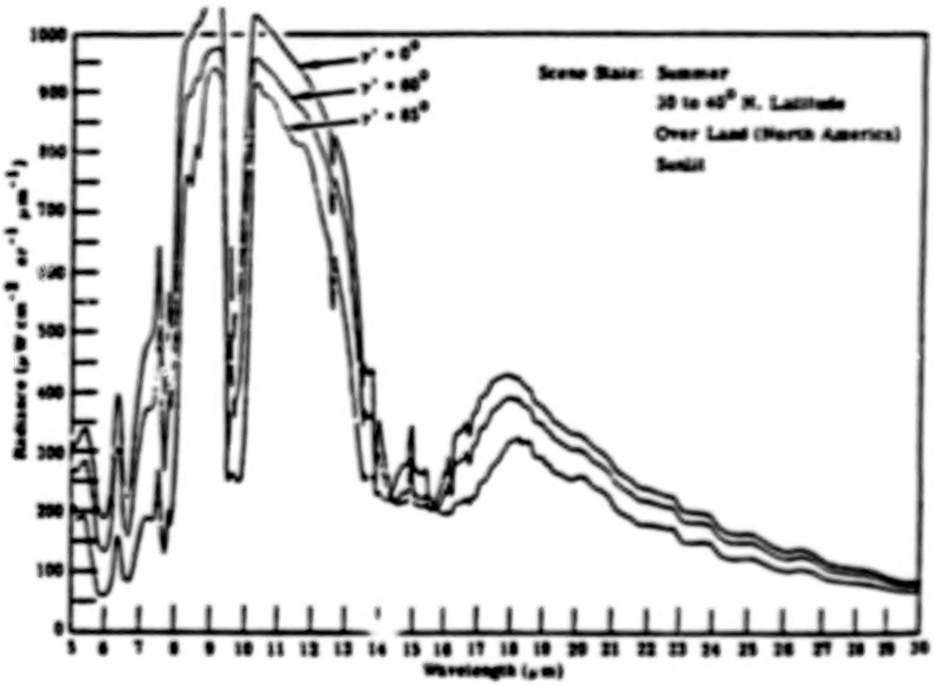
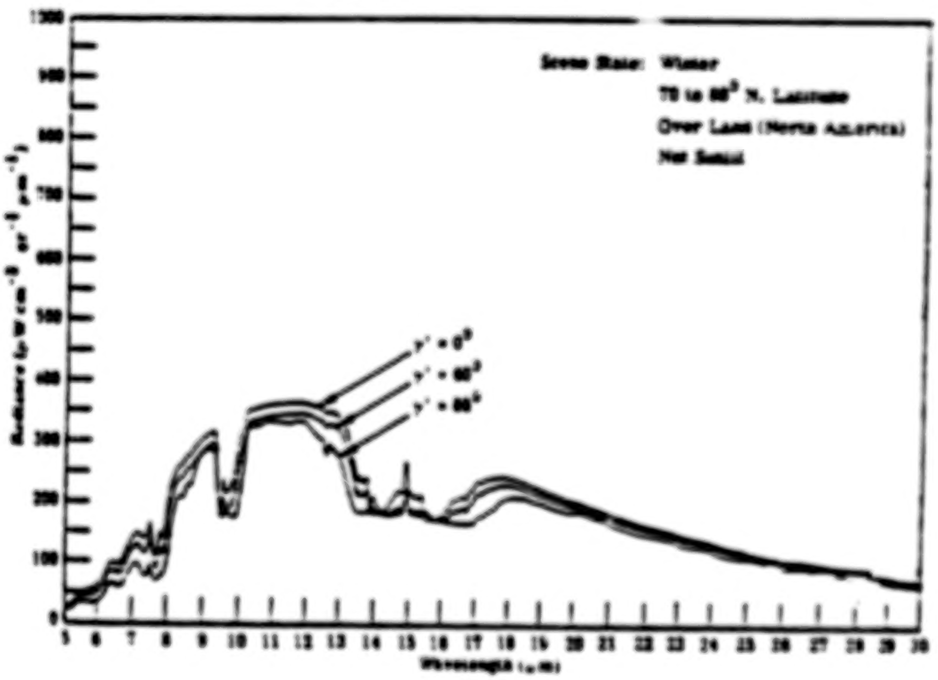
LOW TRAN CALCULATIONS OF THE EARTH'S RADIANCE



SUMMER, 30 TO 40° N. LATITUDE, OVER LAND, SUNLIT



WINTER, 70 TO 80° N. LATITUDE, OVER LAND, NOT SUNLIT

Power Densities as Function of Altitude for Wavelength Band 8-13 μm

Altitude	Θ_M	P/A_S (W/m^2) Summer	Winter
200 miles	72^o	134.13	45.27
300	68	127.52	43.04
622	59	110.05	37.14
932	54	96.82	32.68
1500	46	77.46	26.14
2000	42	64.94	21.92
22,996	26.8	31.17	10.52

Power Densities as a function of Altitude calculated with these spectral radiance from the preceding two graphs. Θ_M is the FOV needed by the receiver to capture all of the earth radiation.

The original plan of attack was to fabricate the rectennas at 1.0 mm wavelengths and then scale and design for 100 μm wavelengths and ultimately for 10 μm wavelength operation.

The problem was approached by first looking at the antenna and the diode separately before attempting to fabricate the rectenna.

The idea of free space power transmission makes the millimeter wave rectennas a goal by themselves. Semiconductor rectifying elements should be used instead of the metal-oxide-metal rectifiers which were intended for use in the infrared region.

SCALING THE LOW FREQUENCY (2.45 GHz) RECTENNAS FOR OPERATION IN THE MMW OR INFRARED REGIONS IS NOT STRAIGHT FORWARD.

1) RECTIFYING ELEMENTS BECOME INEFFICIENT.

   - PRESENT SEMICONDUCTOR DEVICES WILL ONLY WORK UP TO THE 100'S OF GHz.

   - MOM DIODES ARE THE BEST (ALBEIT INEFFICIENT) CHOICE FOR HIGHER FREQUENCY WORK.

2) THE ANTENNA RECEPTION BECOMES COMPLICATED.

   - AT SOME POINT IN THE MMW REGION IT BECOMES IMPRACTICAL TO ATTACH DIODES TO THE INDIVIDUAL ANTENNAS.

   - THE RECTENNAS WILL HAVE TO BE MADE ON SEMICONDUCTOR SUBSTRATES WHICH ARE ELECTRICALLY THICK.

   - ANTENNAS ON FINITE THICKNESS DIELECTRIC SLABS WITHOUT GROUND PLANES ARE NOT WELL UNDERSTOOD.

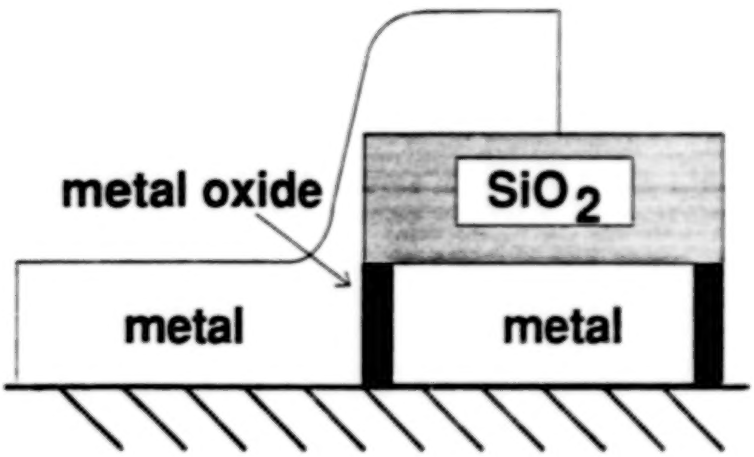
   - THIS TYPE OF ANTENNA CANNOT EASILY BE MODELED AT X-BAND. THE MEASUREMENTS SHOULD BE MADE IN THE MMW REGION.

Georgia Tech MOM Diode Work

Metal-Oxide-Metal (MOM) diodes have been made at Georgia Tech following the work of Heiblum, et.al.

They have developed a method to get a thin oxide layer and a small junction area.

The technique is based on building the diode laterally instead of vertically.



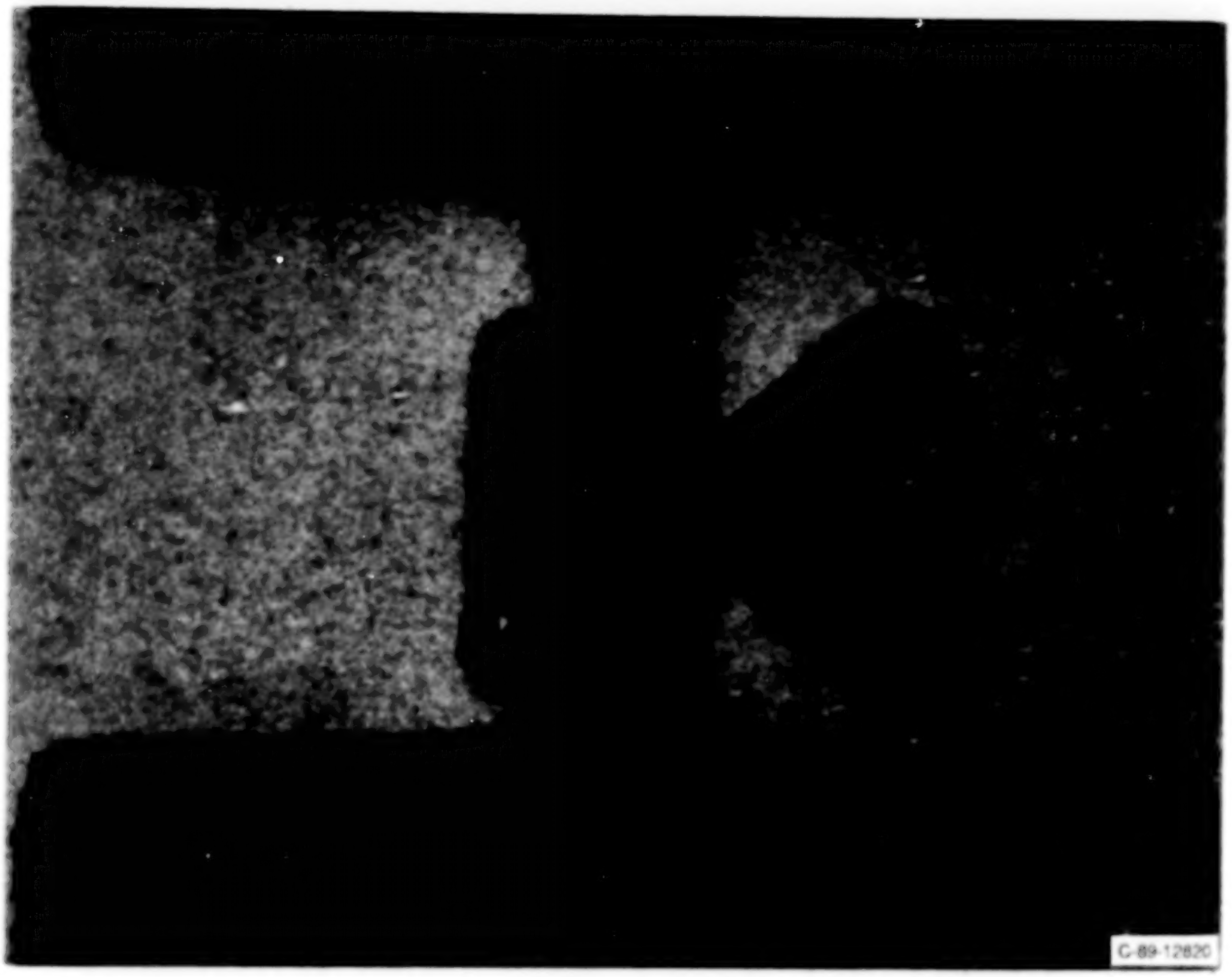
Structure of the Edge MOM Diode

To get extremely thin (10-50 A) oxide layers an equilibrium process of sputter etch and oxidation is used.

Georgia Tech has made Nickel-Nickel oxide - Nickel and Nickel - Nickel oxide - Bismuth diodes.

The nickel was allowed to oxidize in the atmosphere.

In both cases the symmetric I-V curves where obtained indicating that a self biasing rectifying circuit would be needed in order to improve the efficiency.



MOM DIODE FABRICATED AT GEORGIA TECH

Metal-Oxide-Metal Diode - Theoretical Consideration

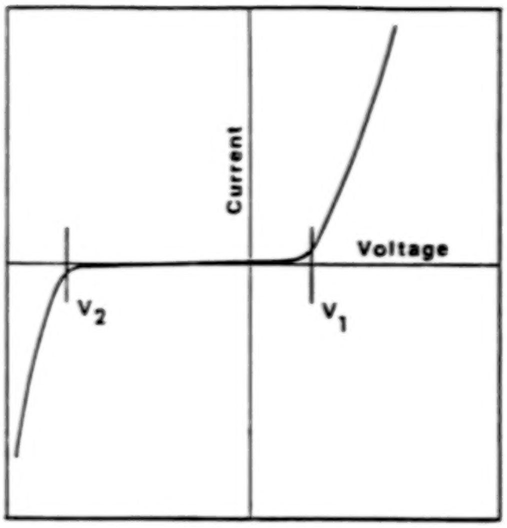
The thickness of the oxide layer can be estimated from the transit time of the electroncs through the oxide.

Transit Time	Oxide Layer
10^{-14}s	10 A
10^{-13}s	100 A

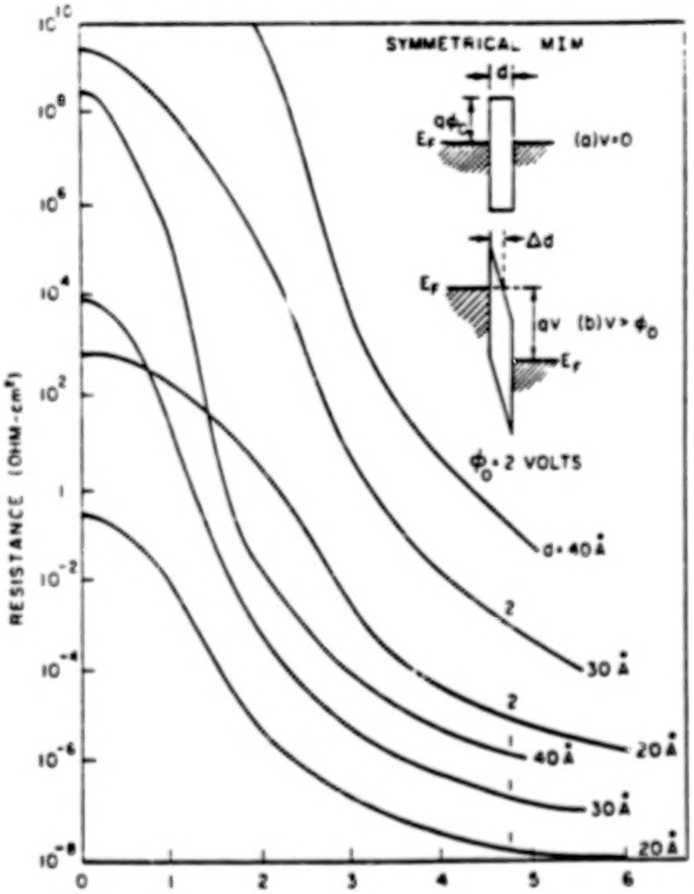
The order of magnitude of the junction size can be estimated from the RC-product for operation in the 10^{-14} - 10^{-13} sec range.

Junction area $0.1\ \mu m^2$

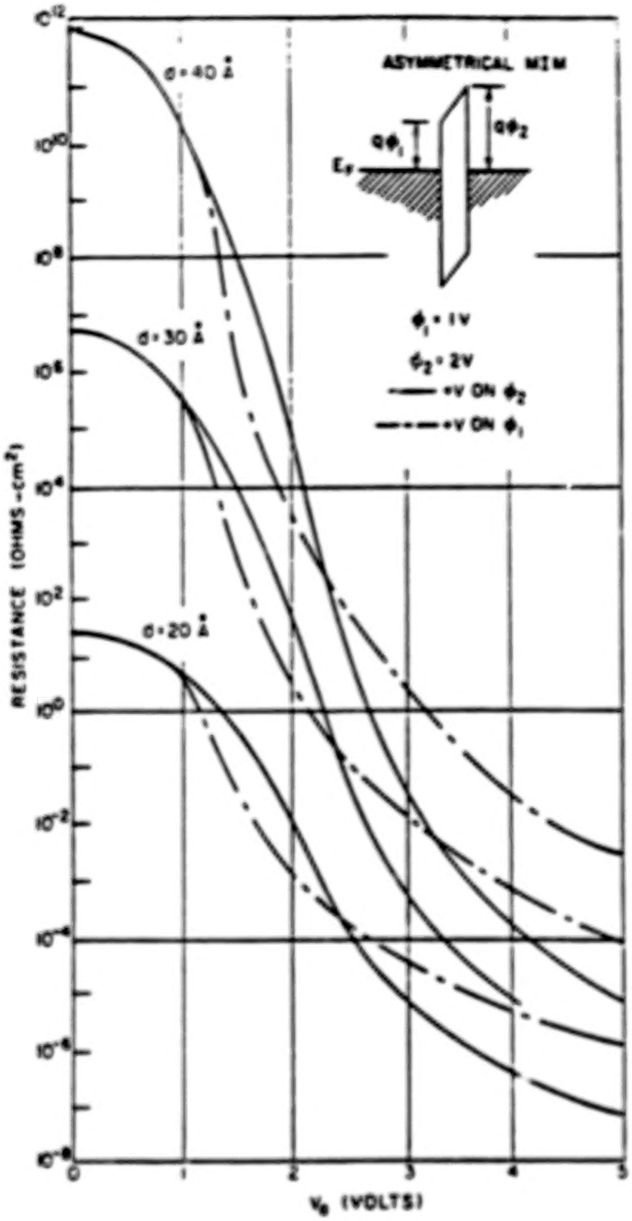
For a 10 A thick, $0.1\ \mu m^2$ device capable of handling 10^4 A/cm^2 at 1 volt, the power handling capability is estimated to be 10^{-6} watts.



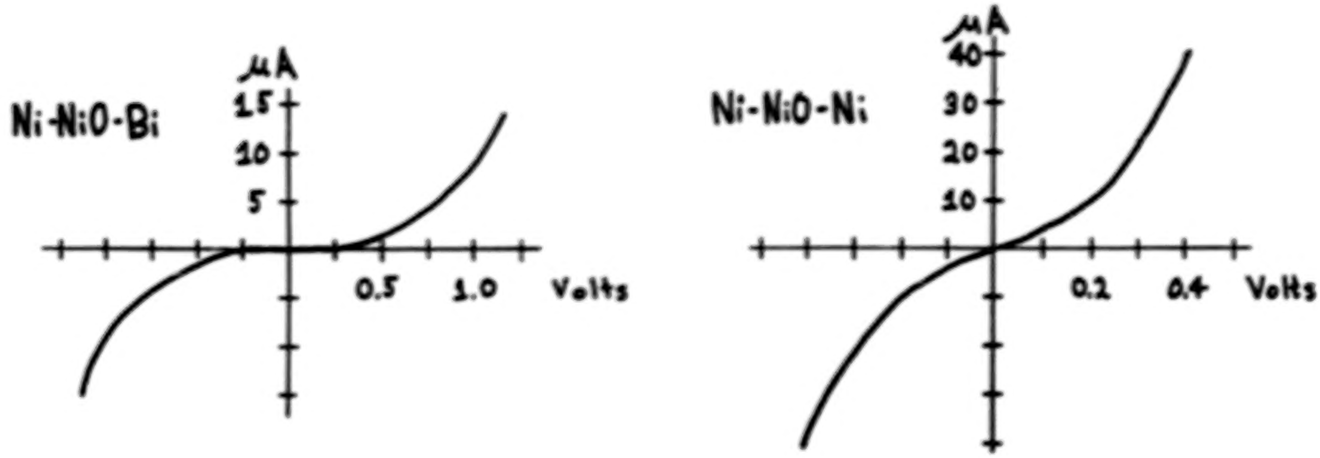
**IDEAL CURRENT - VOLTAGE RELATIONSHIP
FOR RECTIFYING DIODE**



**R-V CURVE FOR THE SYMMETRIC MOM DIODE IS VERY DEPENDENT
ON THE OXIDE THICKNESS. (AFTER SIMMONS).**



ASYMMETRIC MOM STILL HAS VERY SYMMETRIC R-V (AND THUS I-V) CURVES. (AFTER SIMMONS).



I-V CURVES FOR THE MOM DIODES FABRICATED AT GEORGIA TECH. NOTE THAT BOTH THE SYMMETRIC AND ASYMMETRIC MOM DIODES HAVE SYMMETRIC I-V CURVES.

ALTERNATIVES TO THE CONVENTIONAL MON DIODE

1) APPLY THE BARRIER LAYER WITH A LANGMUIR-BLODGETT FILM.

   - THIS ADDRESS THE DIFFICULTY OF PRODUCING A PIN HOLE FREE OXIDE LAYER THAT IS ONLY TENS OF ANGSTROMS THICK.

   - THE LANGMUIR-BLODGETT FILM IS A CONTINUOUS ORGANIC FILM ONLY ONE MOLECULE LAYER THICK.

2) SEMICONDUCTOR VERTICAL STRUCTURE TUNNEL DIODES.

   - THESE HAVE A BAND STRUCTURE VERY SIMILAR TO THE MOM DIODE, ONLY THESE CAN BE FABRICATED WITH EXISTING SEMICONDUCTOR PROCESSES.

3) SEMICONDUCTOR QUANTUM WELL DEVICES.

   - THESE DEVICES HAVE VERY NONLINEAR I-V CURVES. THEY EVEN CONTAIN A NEGATIVE RESISTANCE REGION WHICH MIGHT HAVE SOME APPLICATION FOR THE RECTIFICATION PROBLEM. THE ALTIMATE SPEED OF THESE DEVICES IS NOT KNOWN BUT IT IS PREDICTED THAT THEY WILL WORK UP TO 10^{13} Hz.

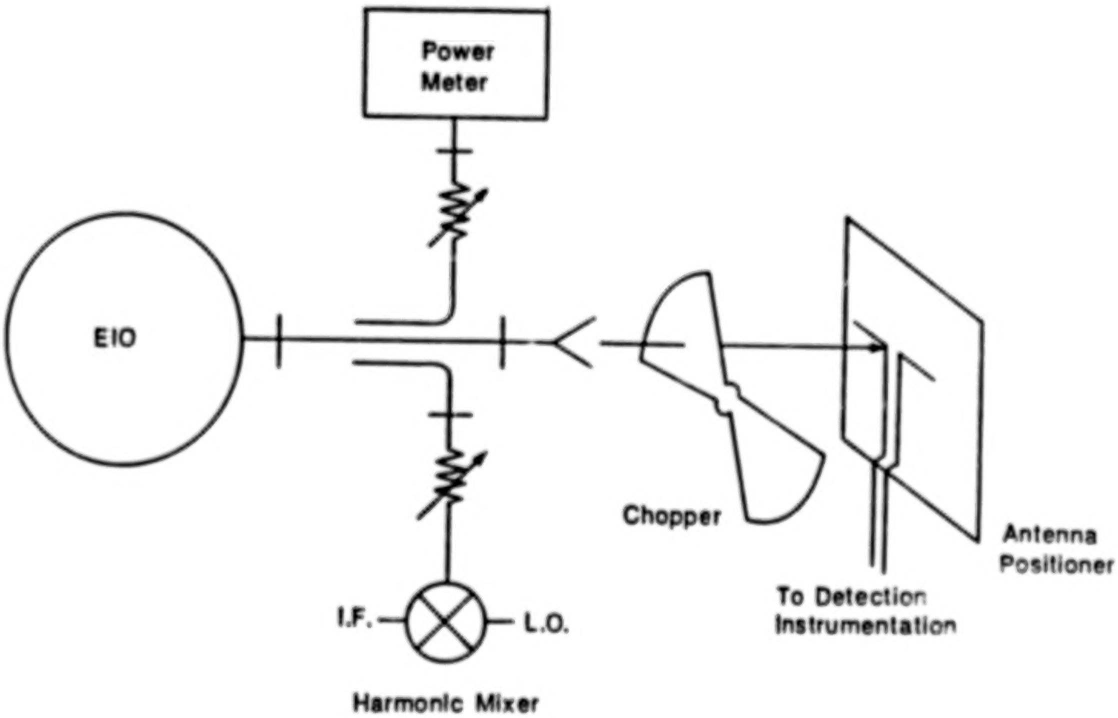
GEORGIA TECH SUBSTRATE MOUNTED ANTENNA WORK

BASIC CONFIGURATION IS A DIPOLE ANTENNA ON AN ELECTRICALLY THICK SUBSTRATE.

A CALIBRATED BISMUTH BOLOMETER IS THE DETECTOR.

WORKING AT 230 GHz (1.3 MM WAVELENGTHS) HAS ITS ADVANTAGES AND DISADVANTAGES:

- THE COMPLETE FAR FIELD ANTENNA RANGE CAN BE PLACED ON TOP OF AN OPTICS TABLE.
- SCATTERING FROM THE ANTENNA POSITIONER AND FROM THE EDGES OF THE SUBSTRATE WHICH HOLDS THE ANTENNA IS A MAJOR PROBLEM.
- STRAY PICKUP ON THE LEADS WHICH CONNECT ANTENNA TO THE EXTERNAL CIRCUITS MUST BE ELIMINATED.
- THE ANTENNA MUST REMAIN STATIONARY (TO WITHIN $\lambda/16$ OR 80 μM UNDER ROTATION IN ORDER TO ASSURE IT IS SUBJECTED TO A CONSTANT INCIDENT FIELD.



LAYOUT OF TABLE TOP ANTENNA RANGE

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PHOTOGRAPH OF THE TABLE TOP FAR-FIELD RANGE USED FOR MAKING THE FIELD PATTERN MEASUREMENTS OF THE SUBSTRATE MOUNTED ANTENNAS.

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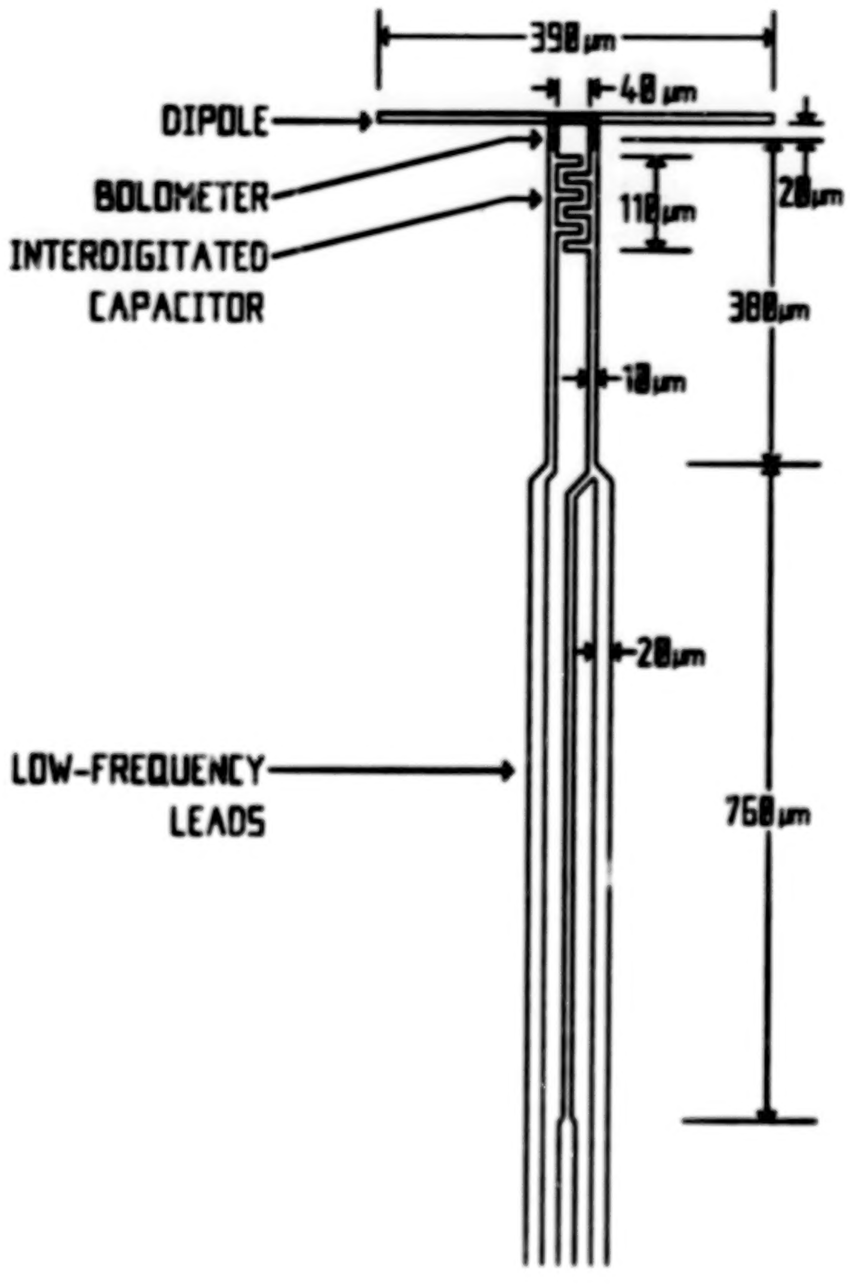
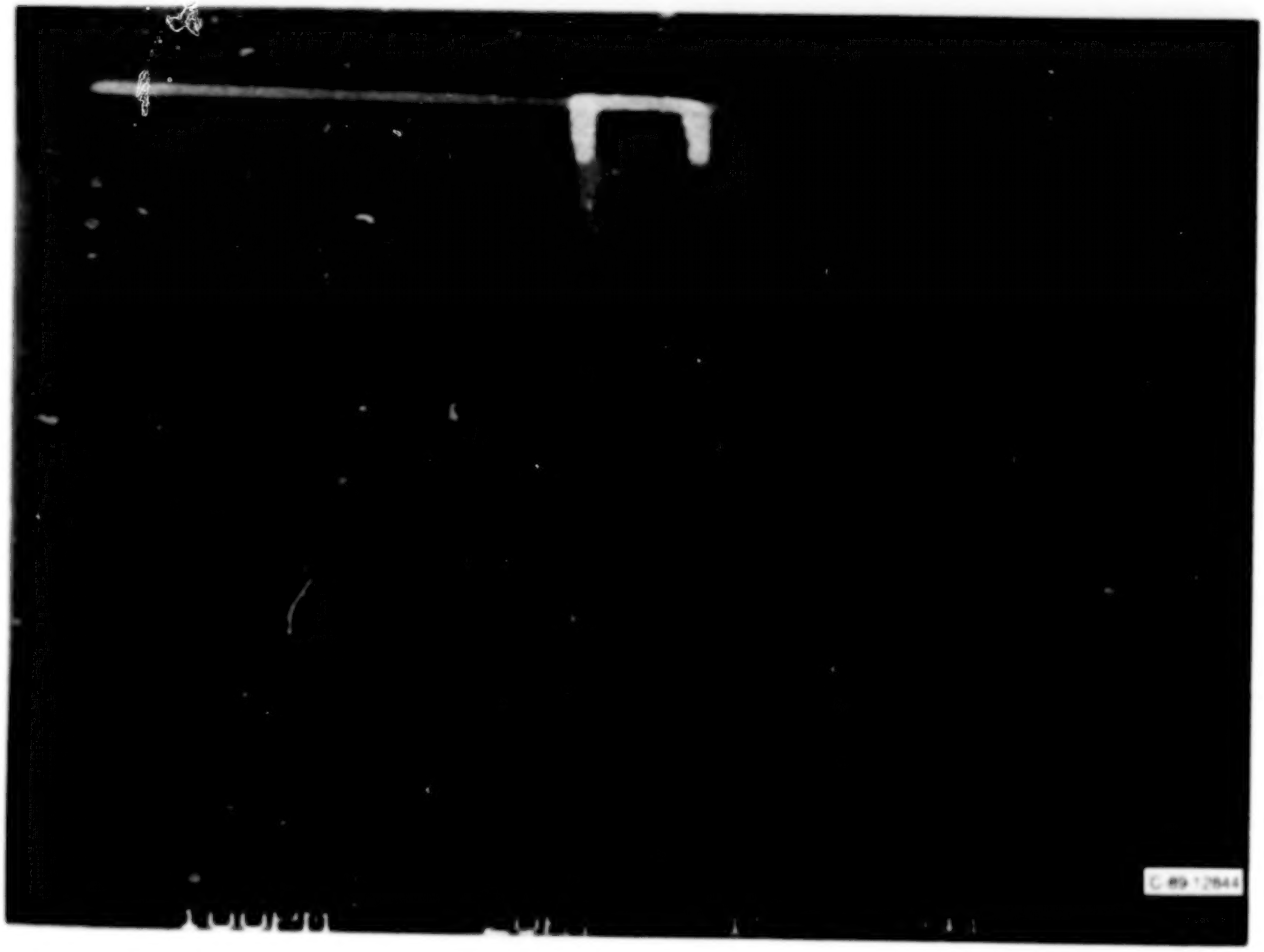
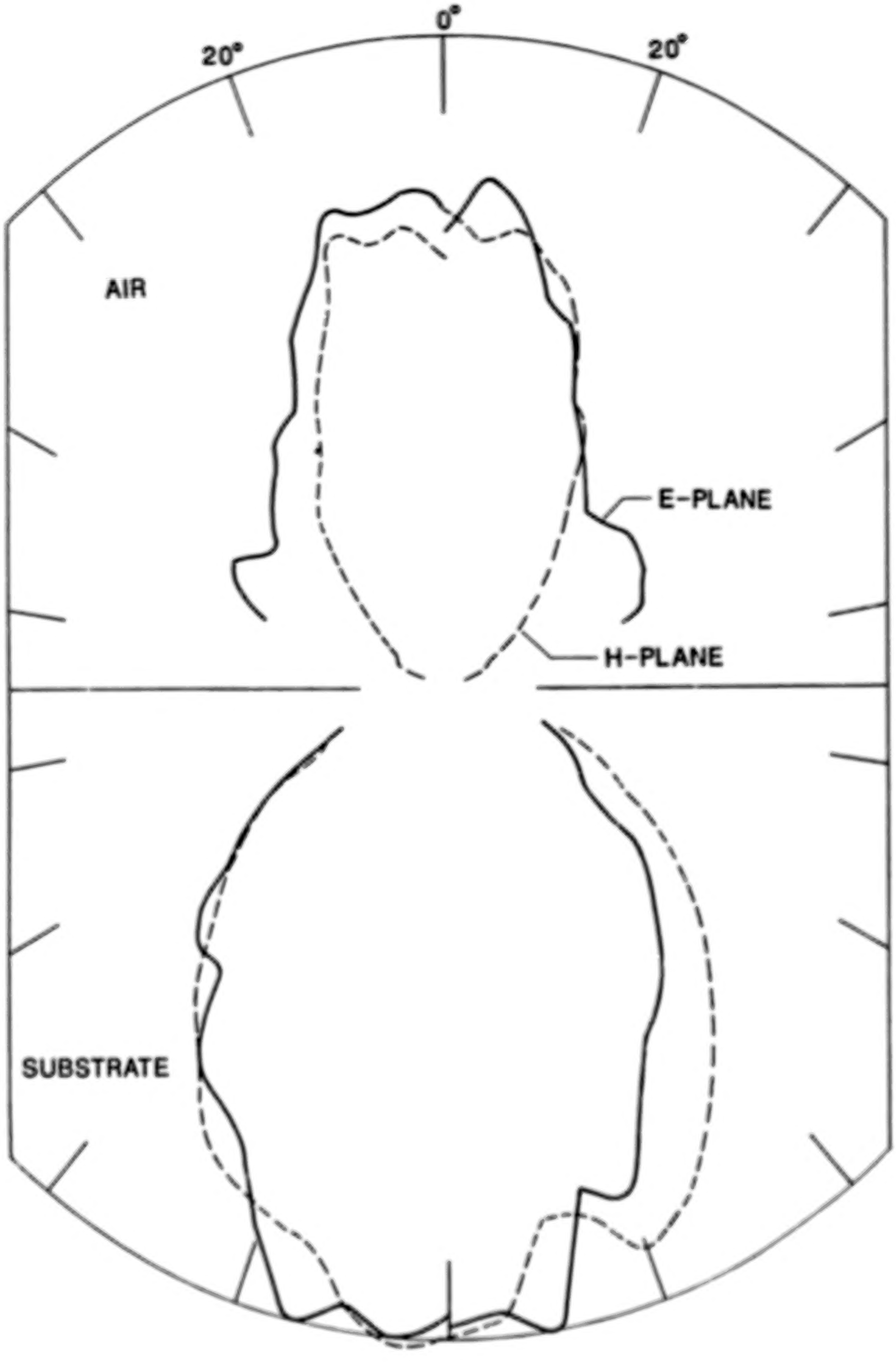


LAYOUT OF THE ANTENNA STRUCTURE.



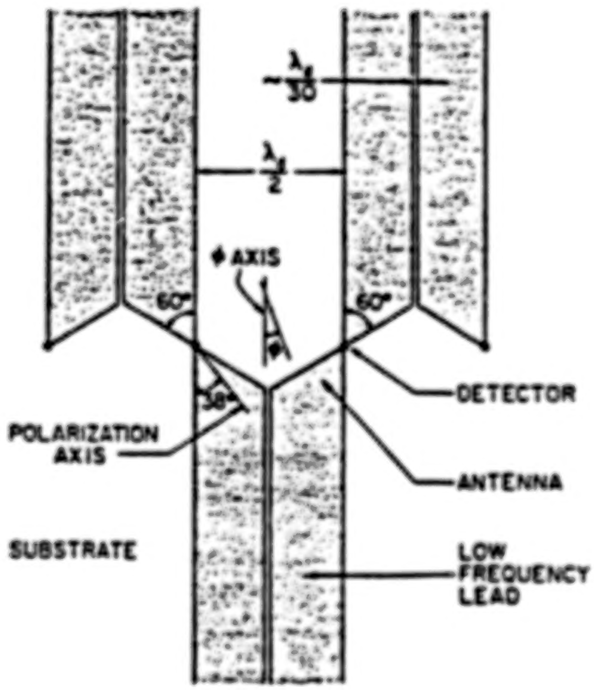
SCANNING ELECTRON MICROGRAPH OF THE ANTENNA STRUCTURE.



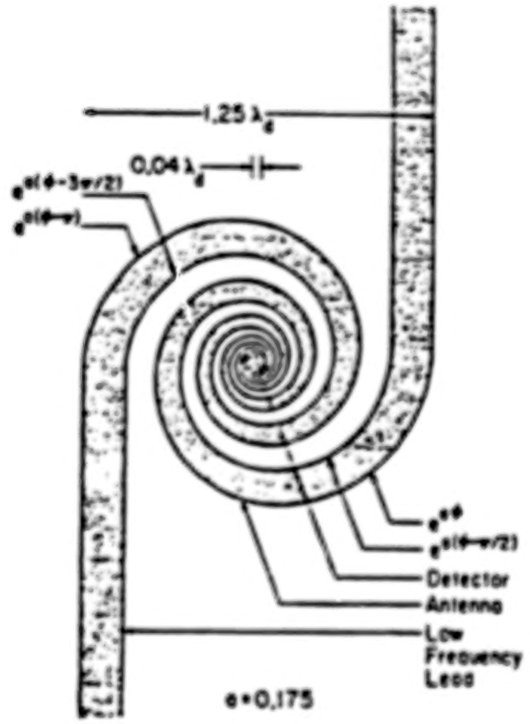
FIELD PATTERNS FOR A SUBSTRATE MOUNTED ANTENNA MADE AT GEORGIA TECH.

Other Types of Substrate Mounted Antennas

Bow-tie

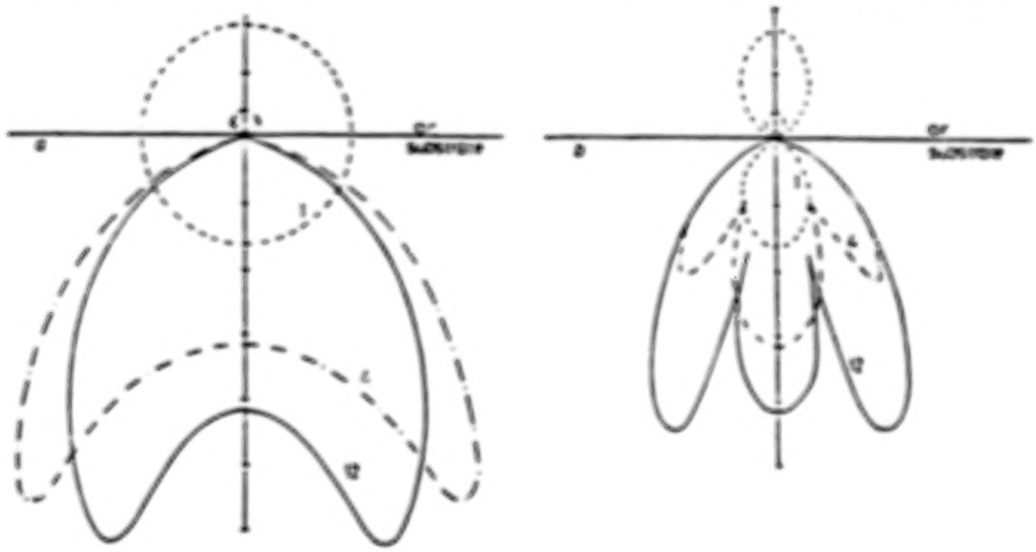


Spiral



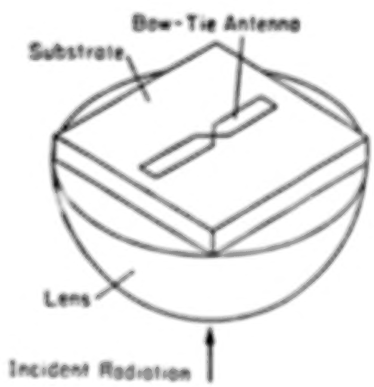
P.P.T. TONG, PH.D. THESIS, CALIF INST TECH, 1985

A GENERAL PROPERTY OF THE SUBSTRATE MOUNTED ANTENNAS IS THAT THE ANTENNA PATTERN IS HEAVILY WEIGHTED INTO THE SUBSTRATE.



C.R. BREWITT-TAYLOR ET AL, ELEC LETT, VOL 17, PG 729.

WE CAN USE THIS PROPERTY TO PERFORM TASKS, SUCH AS FOCUSING, WITH THE SUBSTRATE.



D.B. RUTLEDGE ET AL, INFRARED AND MM WAVES, VOL 10, PG 1.

DIRECTIONS FOR FUTURE WORK

1) UNDERSTAND THE RECEPTION OF THE SUBSTRATE MOUNTED ANTENNAS ON ELECTRICALLY THICK SUBSTRATES.

2) LOOK AT WAYS TO INCREASE THE RECEPTION OF TAKING ADVANTAGE OF THE ELECTRONICALLY THICK SUBSTRATES.

3) INTEGRATE A SEMICONDUCTOR DIODE WITH THE SUBSTRATE MOUNTED ANTENNA.

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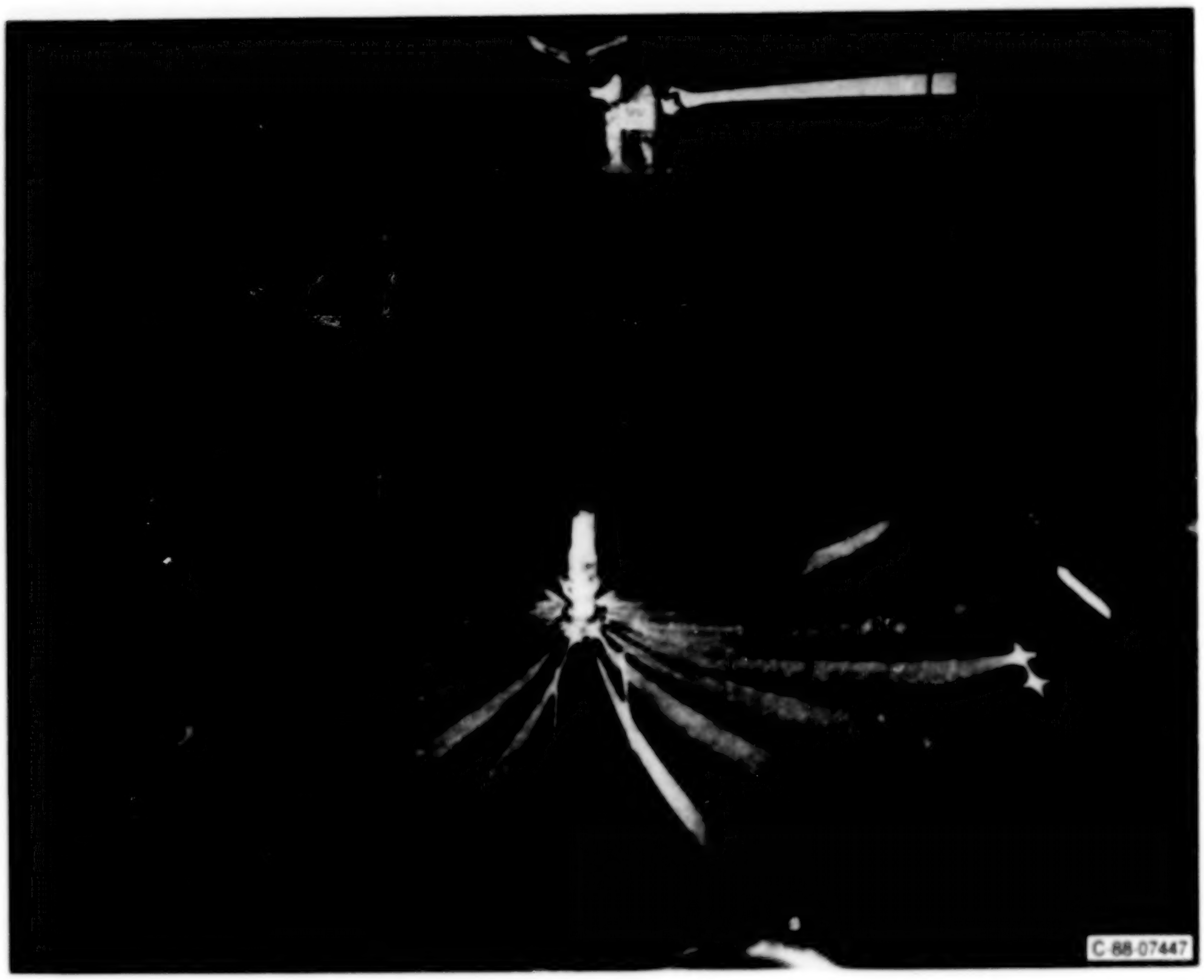
LARGE SPACE SYSTEMS ANTENNA TECHNOLOGY

Thomas G. Campbell
NASA Langley Research Center
Hampton, Virginia 23665



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LESSONS LEARNED

- Build accuracy off by factor-of-two.
- Manual adjustment better than spec.
- Finite element model development.
- Antenna pattern calculations OK with notable exceptions.
- Surface RMS - sidelobe relation.
- Near field diagnostics.

CSEI
PROGRAM OBJECTIVE

Develop Large Space Antenna Technology

For Optimizing RF Performance

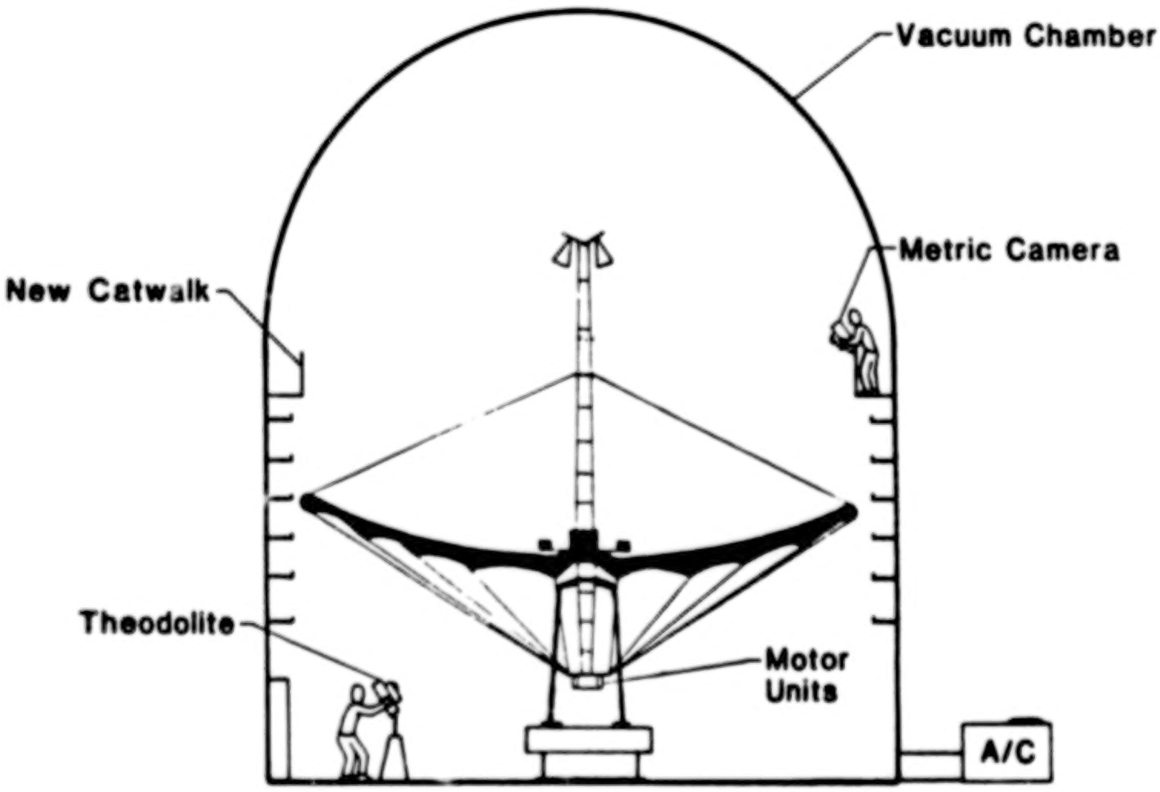
Using An Interdisciplinary Approach.

APPROACH

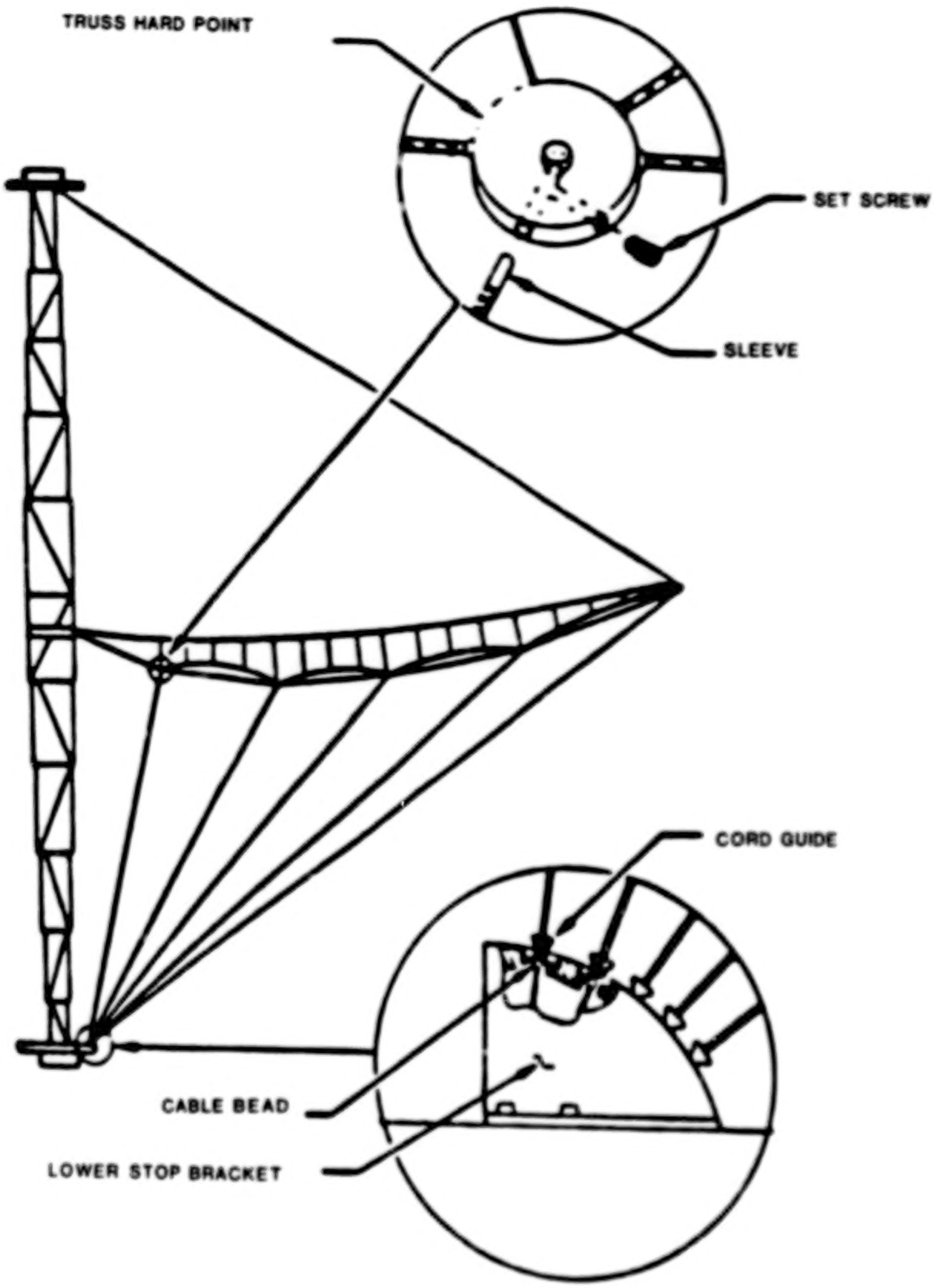
EXTEND 15-METER ANTENNA TESTS TO INCLUDE:

- Surface Control For Reflector Figure Improvement
- Adaptive Feed Techniques For Surface Distortion Compensation
- Integrated Experiments
  - -Structural Dynamics
  - -Electromagnetics
  - -Controls
- Real Time Figure Measurements

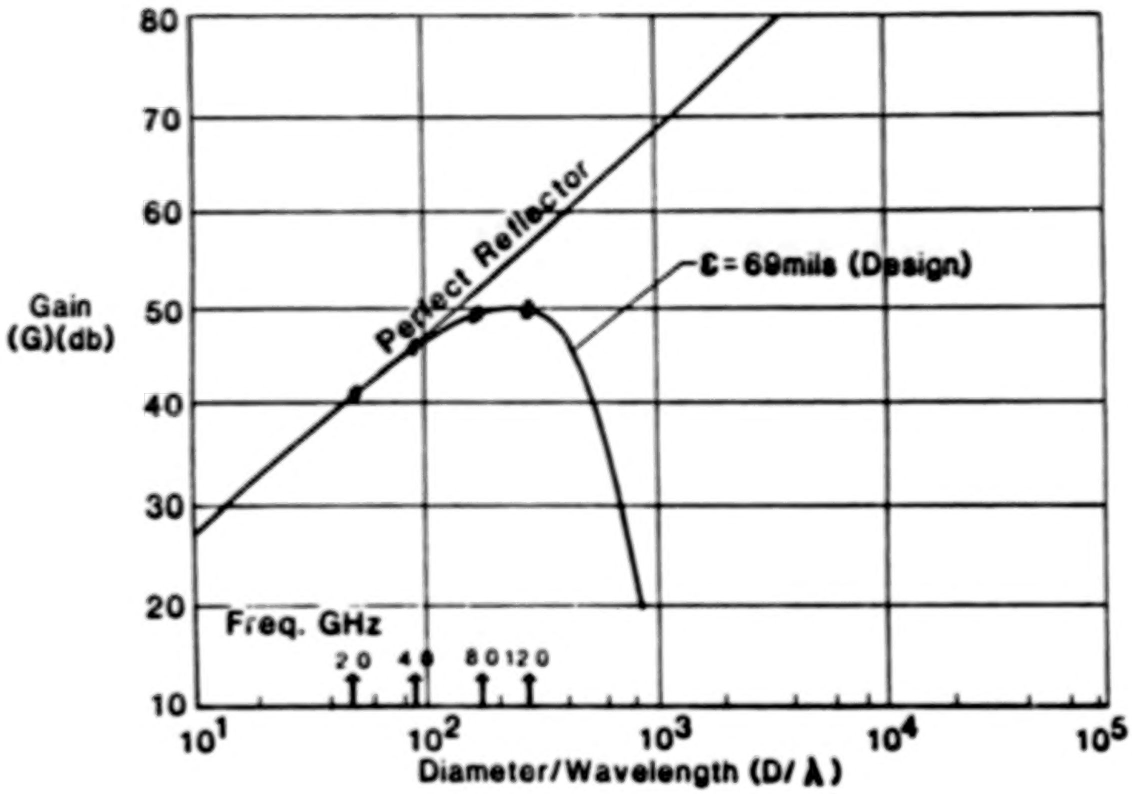
PHASE I TEST FACILITY (Bldg. 1293B)

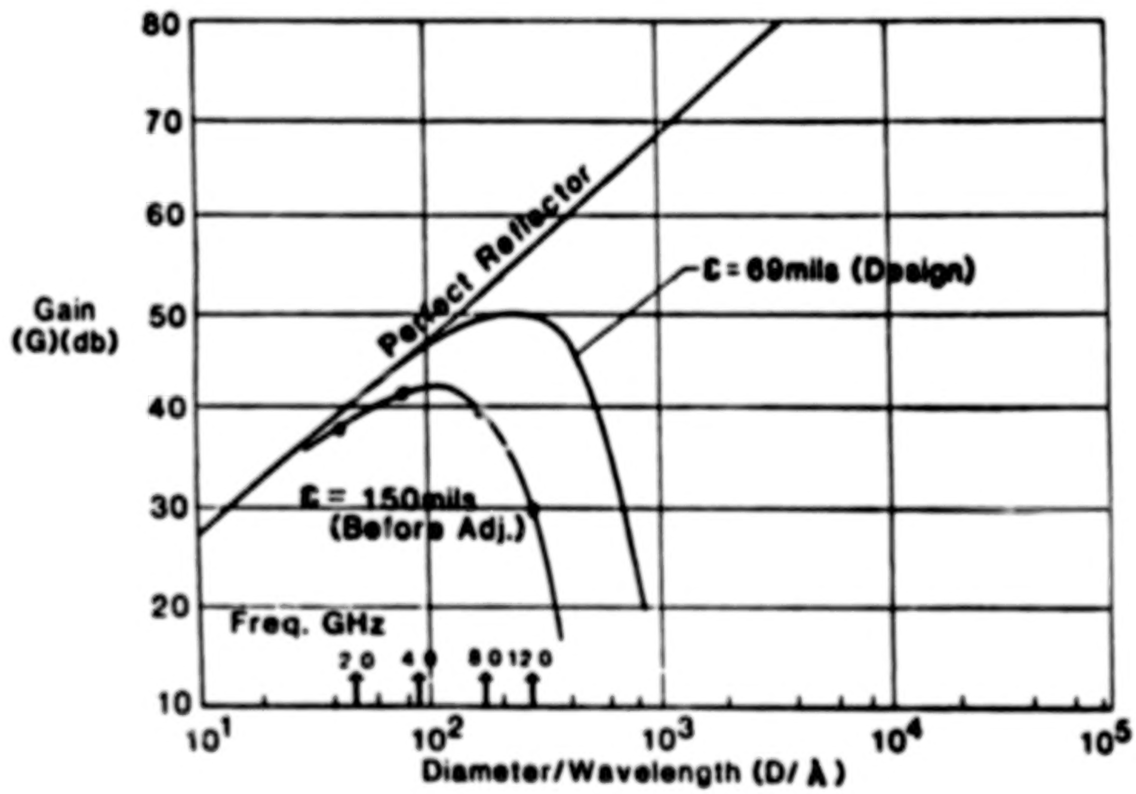


SURFACE CONTROL CORDS

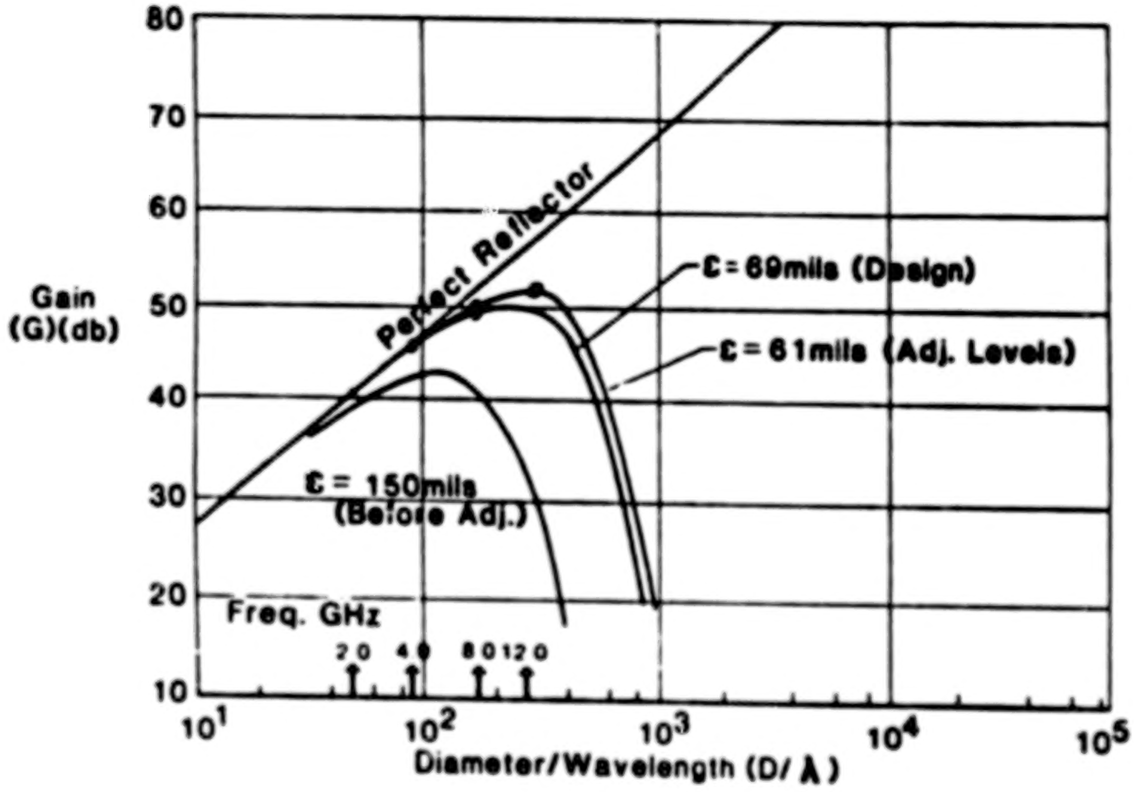


WHAT FREQUENCIES TO USE



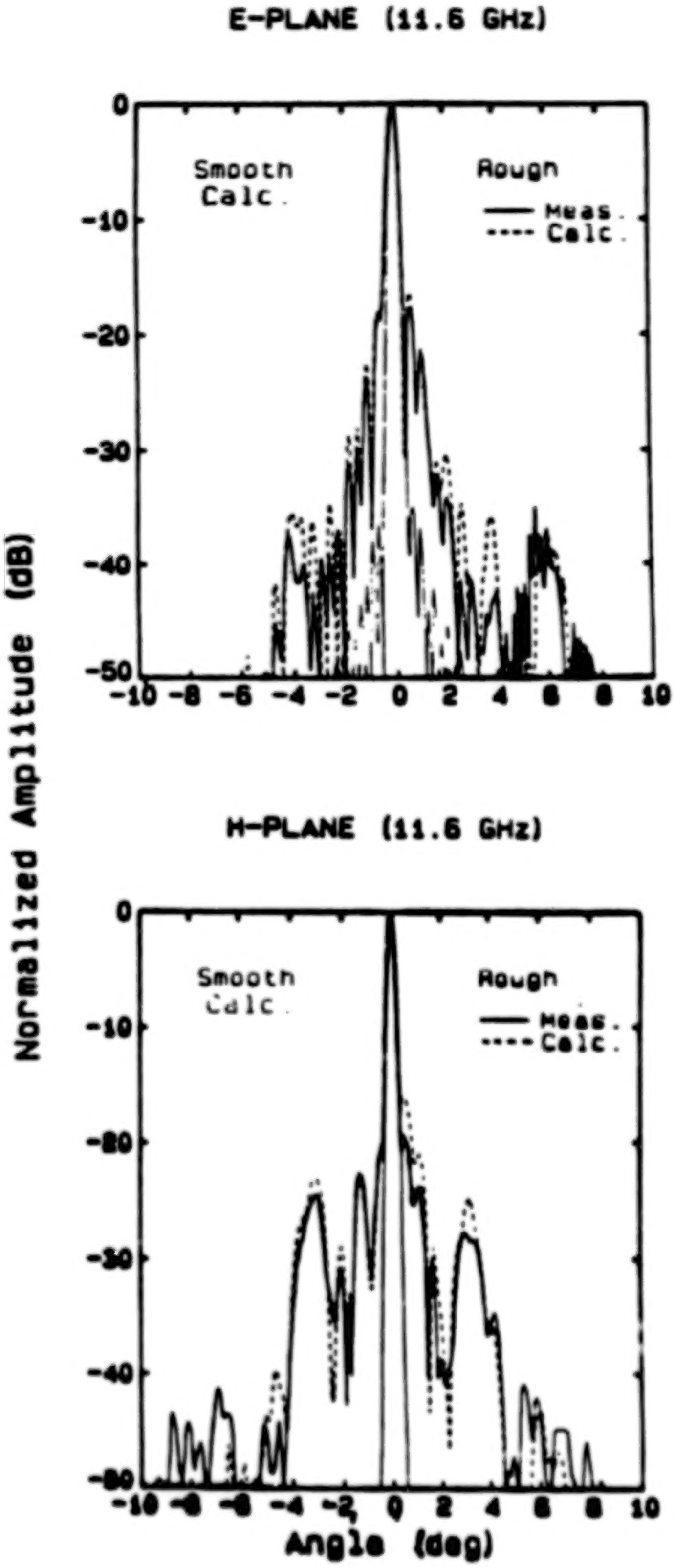


WHAT FREQUENCIES TO USE

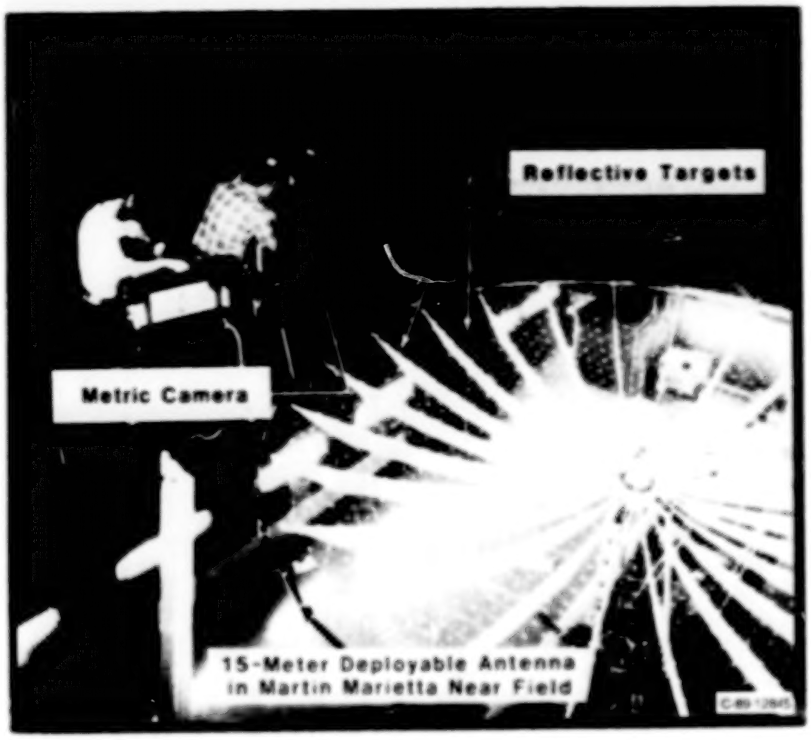


RADIATION PATTERNS FOR HOOP/COLUMN

REFLECTOR ANTENNA



SURFACE CHARACTERIZATION OF LARGE SCALE ANTENNAS



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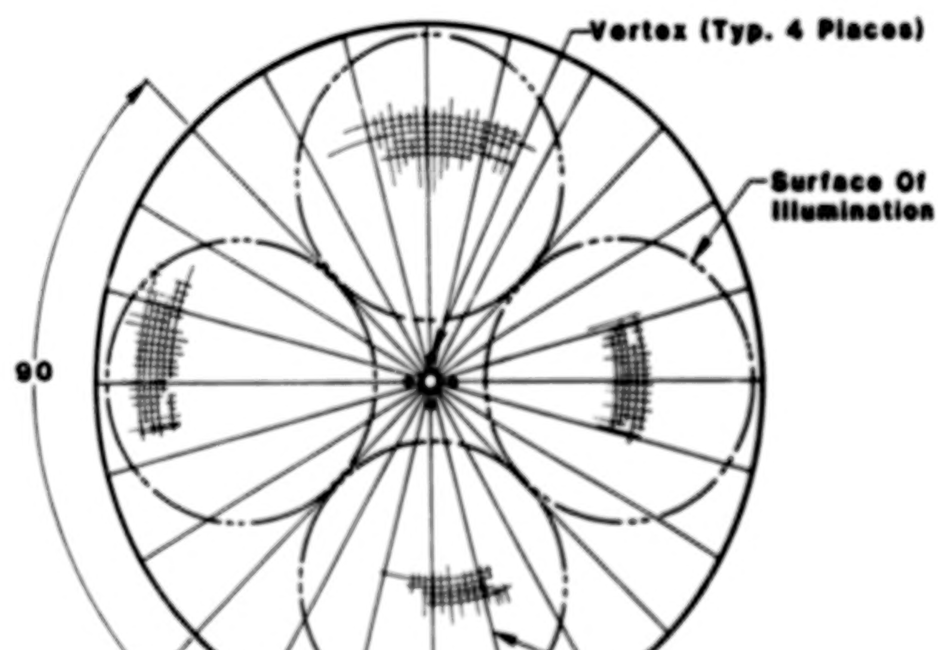
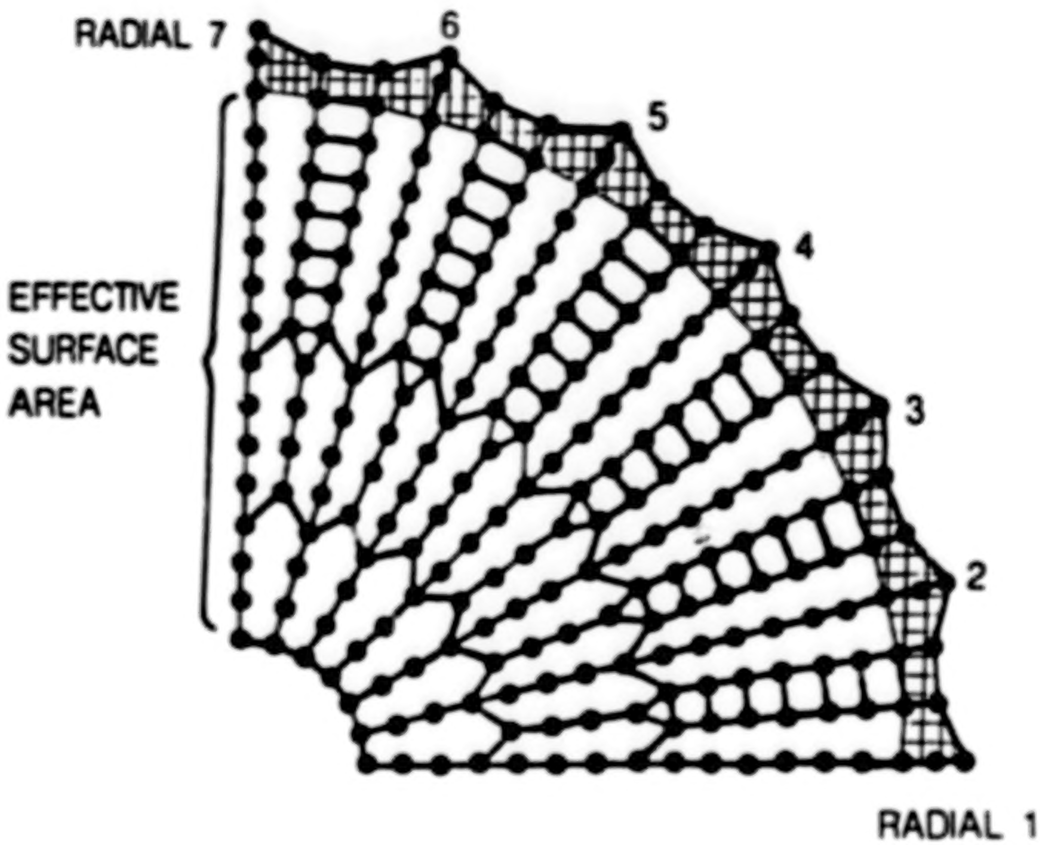
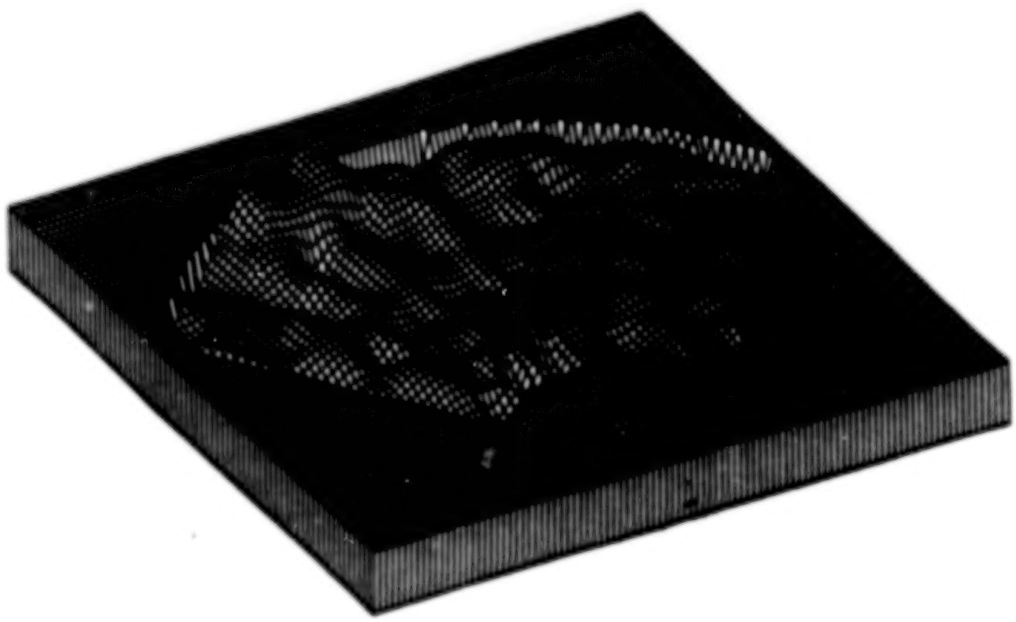
SURFACE-PLAN VIEW

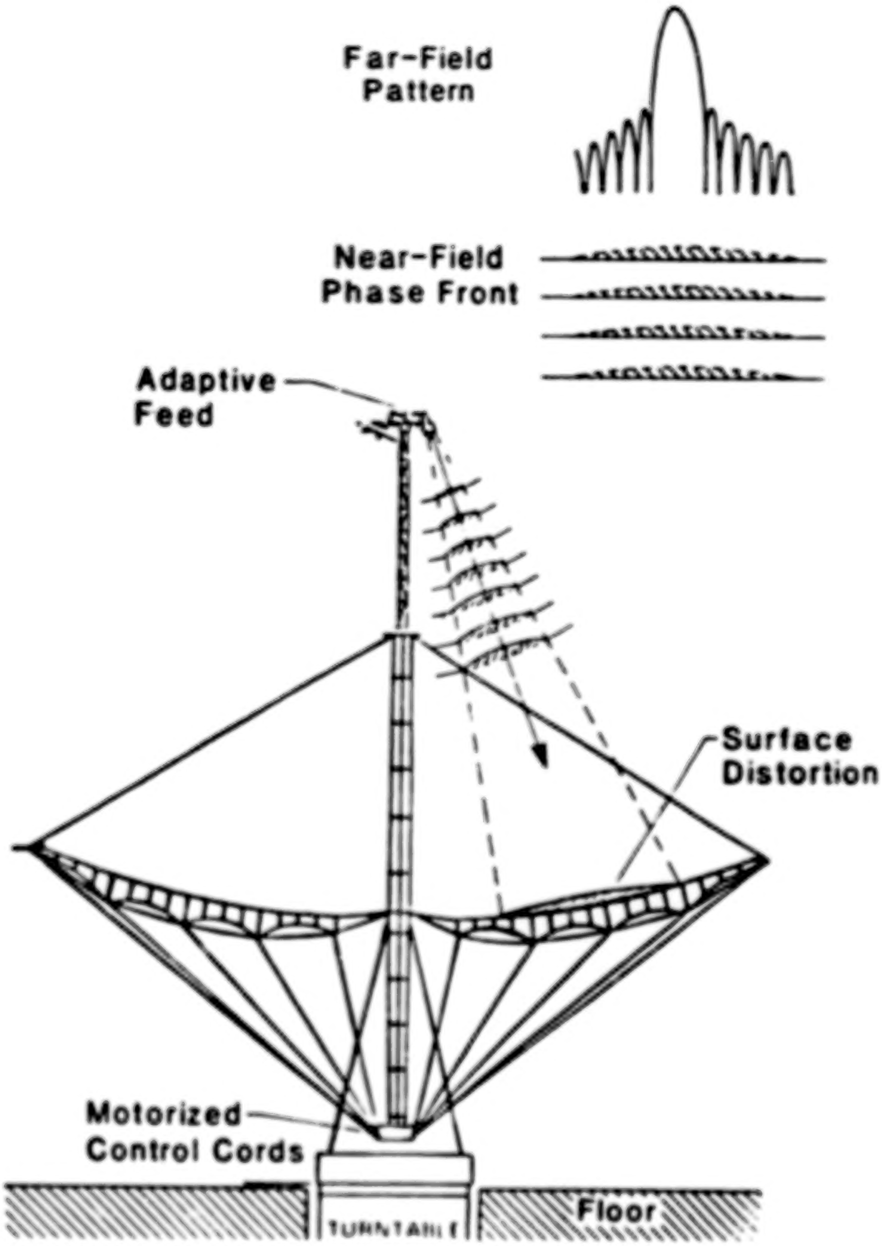


Antenna Surface Target Locations

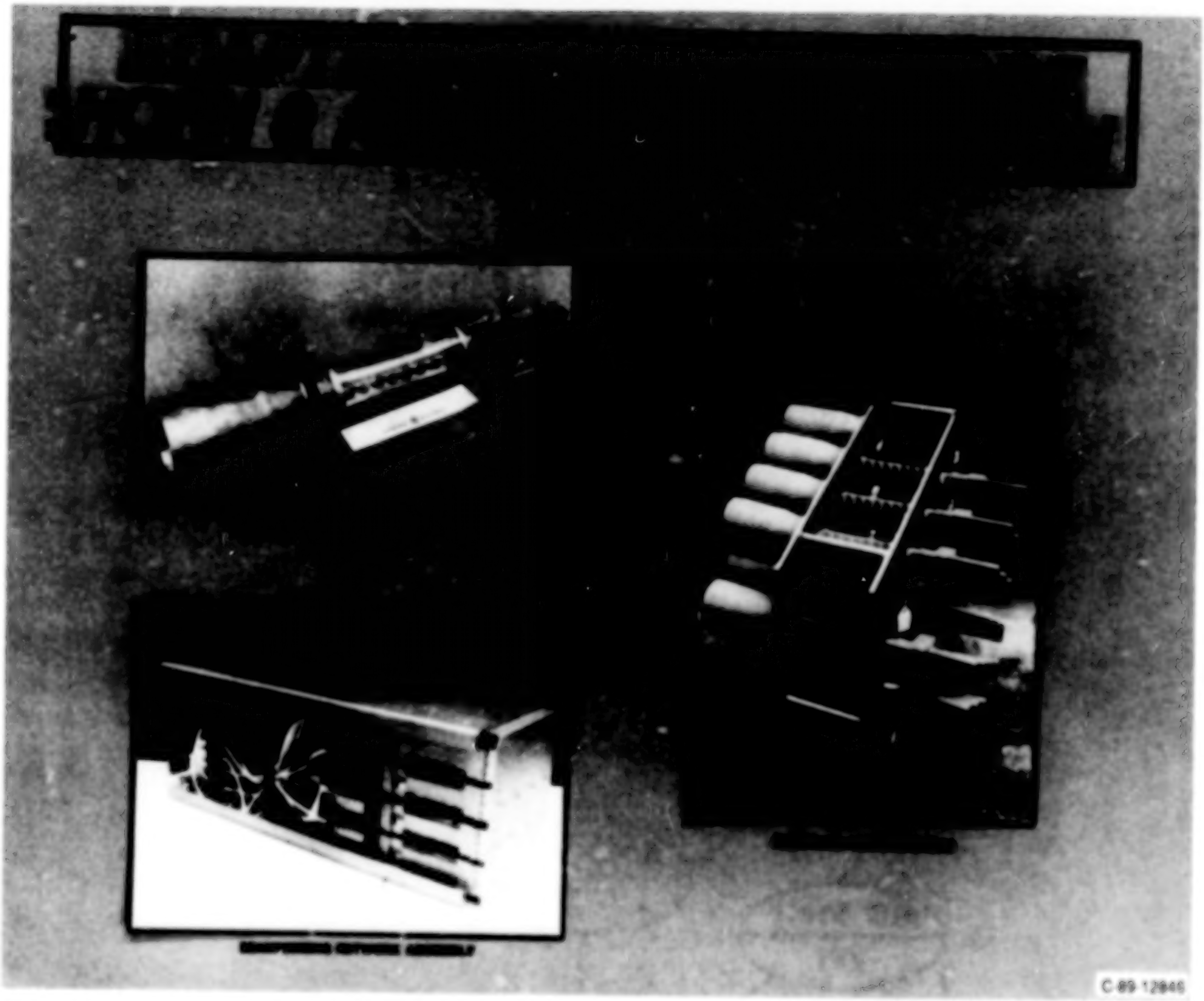


QUADRANT 4 SURFACE SHAPE
(Tie points only)





Far-Field
Pattern
Near-Field
Phase Front
Adaptive
Feed
Surface
Distortion
Motorized
Control Cords
Floor
TURNTABLE



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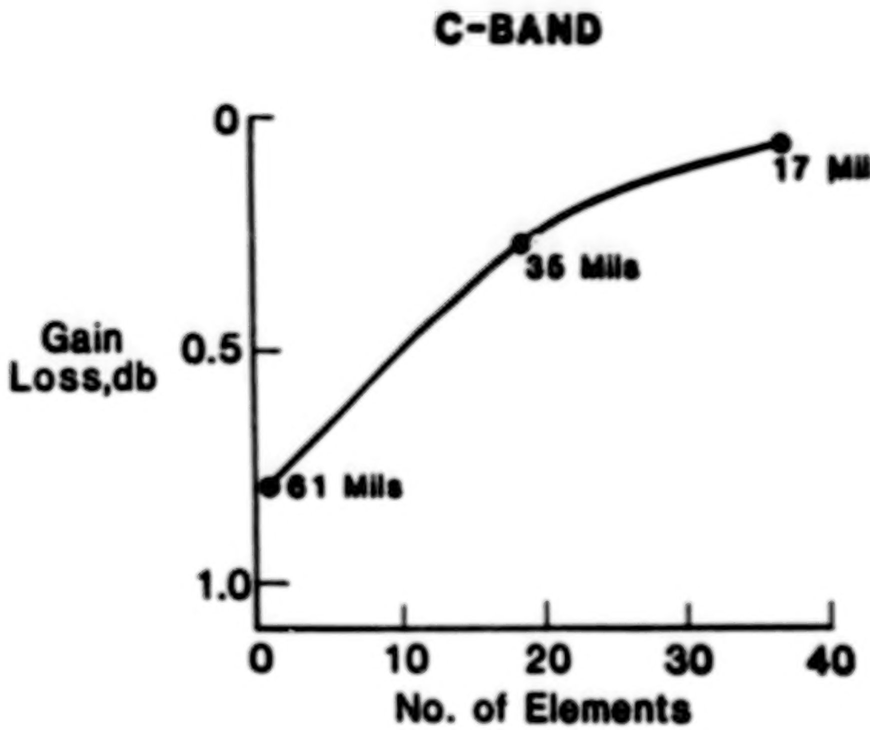
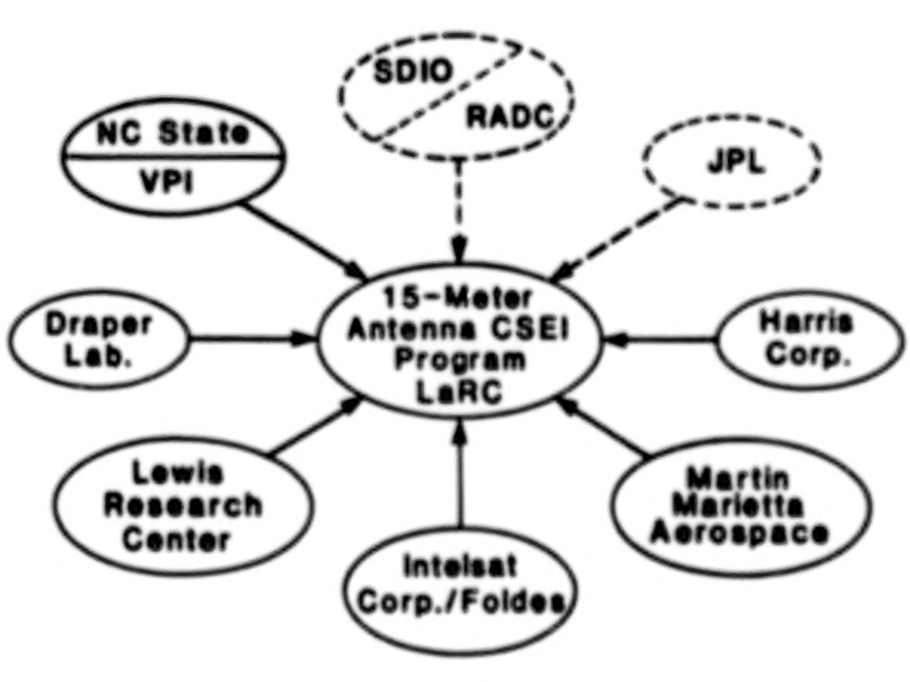
ADAPTIVE FEED COMPENSATION



CSEI OUTSIDE PARTICIPANTS



TECHNOLOGY BENEFITS OF CSEI PROGRAM

- Expand RF Performance Data Base on Large Space Antennas
- Obtain Accurate Evaluation Of Interdisciplinary Analytical Codes
- Development of Surface Control & Adaptive Feed Concepts
- Verification of Design Methodology for Optimizing RF Performance for Large Aperture Systems

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INFLATABLE ANTENNAS FOR MICROWAVE POWER TRANSMISSION

Geoff Williams
L'Garde Inc.
Tustin, California 92680

L'GARDE SPACE INFLATABLES

Various ABRES (IEO, DDT, AMT, AREP, TREP) (1971 through 1978)	Sounding rocket and ICBM flights
Space Defense	
ITV (SD)	Study
Have Busk I (RPL)	Study
Reflectors	
Antenna (NASA)	Study
Antenna (Martin)	Study
VOA (TRW/State)	Study
Solar Concentrator (RPL)	Ground test
SDI - related	
Radiator (AFWAL SDIO)	Ground test
NP. Beam (SAIC LMSC)	Flight test
SRMP (BMO/USASDC)	Flight test
STEP SD (in evaluation)	Flight test

INFLATABLE SPACE STRUCTURES

NASA - antennas

USAF-BMO - decoys

USAF-SD - ITV

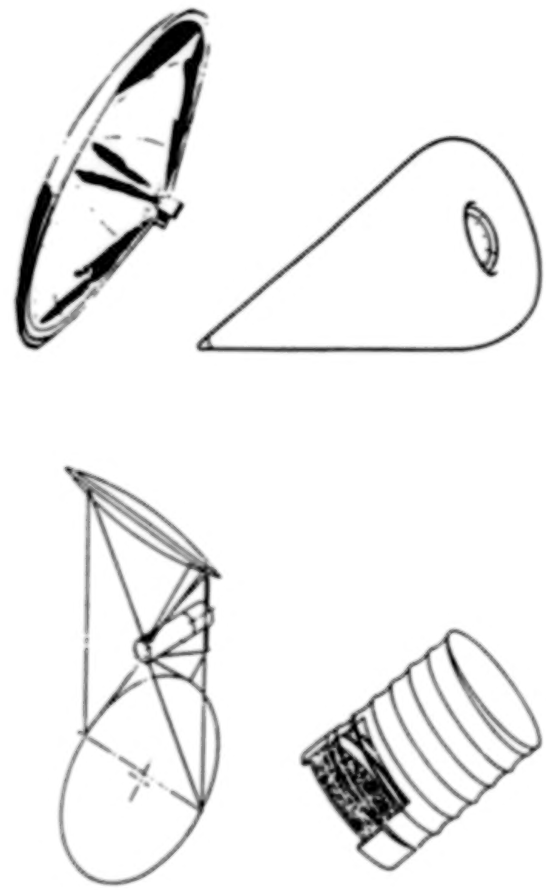
AFRPL - Solar collector

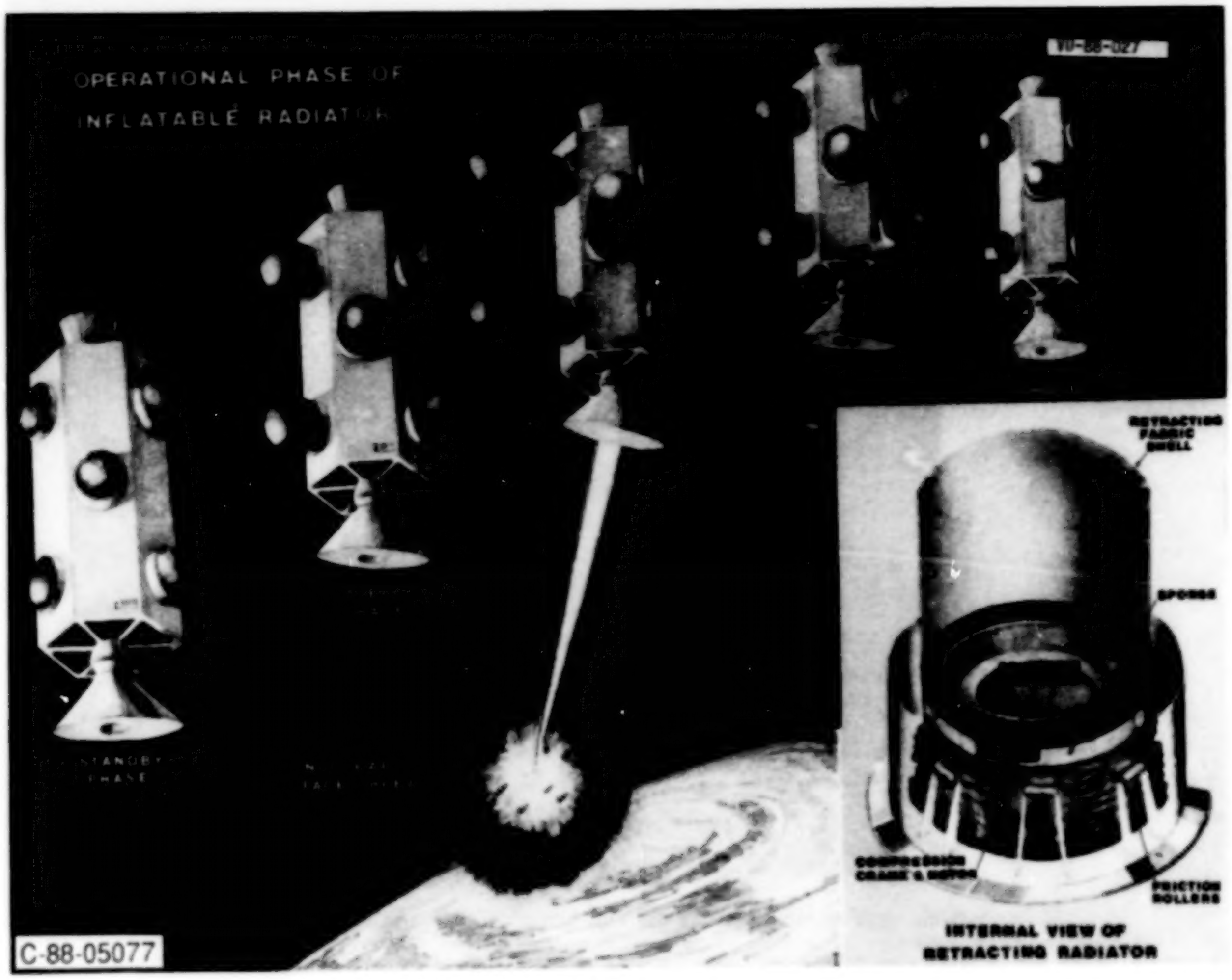
AFWAL - radiator

SDIO - radiator

USASDC - decoys

Aerospace Companies: (TRW, Martin,
MDAC, Avco, MIT/LL)

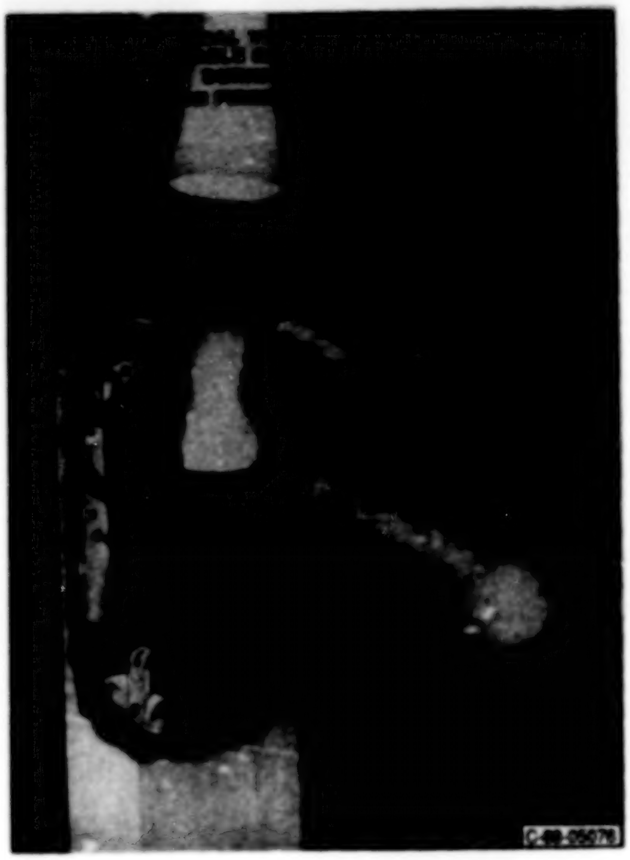




OPERATIONAL PHASE OF THE INFLATABLE RADIATOR

This picture shows the operations phases of a weapon system using the High Power Inflatable Radiator Systems (HIRS) and the insert shows the design of an inflatable radiator. The operation of HIRS is described as follows: In its normal standby phase the inflatable radiator is housed inside the space weapon system to enhance its survivability and to keep it at a temperature where the liquid water, used in the system, will not freeze. In the alert phase a small amount of water vapor is used to inflate the radiator fabric bag at low pressure. This is done to keep the bag from bursting as a result of the high water vapor pressure impulse developed in a short time during the firing phase. In the firing phase the radiator is designed to operate for 2 minutes continuously. This is based on a polar orbit of 100 minutes where the radiator will be ready for use 4 minutes of this time. The radiator system will be capable of dissipation between 10 and 100 megawatts (mw) levels of waste heat. During the cooling phase the waste heat will be dissipated in space by condensation on the inside of the fabric bag. As the vapor pressure subsides a sensor will actuate the retraction mechanism to bring in the bag. A 5.6 psi pressure will be maintained in the bag during retraction in order to keep the bag stable, to facilitate folding the fabric radiator, and to prevent freezing of water on the cold side of the bag. After all the heat is dissipated the bag will be folded and stored in the temperature controlled environment of the spacecraft. The water vapor will have condensed, and the liquid will have been collected and returned to a reservoir to use again.

In the insert the inflatable radiator is shown partially retracted. The fabric bag will be made of a material which has low water permeability, a fabric and seam strength of 500 lbs/linear in., high emissitivity and a low contamination level factor for the space surrounding the weapon system. Water recovery is done by using a sponge to gather the water which has condensed on the sides of the radiator, and then squeezing the sponge into a recovery system which transmits it to a reservoir to be used again. The friction rollers and motor are used to roll in the fabric radiator and then fold it into the spacecraft.



INTERNAL VIEW OF THE INFLATABLE RADIATOR DURING WEAPON FIRING PHASE

This picture shows the internal view of the inflatable radiator during the space weapon's firing phase. The waste heat from the weapon is absorbed by the boiler tubes surrounding it. The water is turned into water vapor at 75°C and then is forced through a vapor/liquid separator where the vapor is directed toward the inflatable fabric radiator and the water is returned to the reservoir. The vapor pressurizes the radiator, which has previously been inflated at low pressure to avoid destroying it during the actual firing phase. The vapor condenses on the radiator wall where it is then sponged up, recovered and returned to the reservoir to be used again. The operational characteristics for the inflatable radiator are as follows.

HIRS TECHNICAL REQUIREMENTS

1. OPERATIONAL RADIATOR DIMENSIONS
   - Dia - 8'
   - Height - 40'
   - Area input opening to radiator is 1/4 total radiator cross sectional area
   - Time expanded in polar orbit is 100 minutes
     - Operational time 4 min
     - Continuous operations 2 min

2. FABRIC REQUIREMENTS
   - Water permeability - as low as possible
   - Tensile strength - 500 lbs/linear inch
   - Temperature - 75°C
   - G Force - max of .1G in space
   - Launch forces will be same as the space shuttle
   - Withstand radiation intensity from the sun as a 6000K Black Body at 1350 W/M^2
   - Minimum contamination leakage
   - Internal pressure - Max 5.6 psi
   - Compatible with water vapor and liquid for long periods of time (10 yr.)

3. RADIATOR must be capable of expanding and contracting in space a minimum of 25 times.
   - Test once a year for 10 years
   - Potential use as a weapon is 15 times

4. SYSTEM WASTE HEAT REQUIREMENTS
   - Operation - 10 to 100 MW

5. TRANSPORTATION - Must be collapsable as cargo to fit into the space shuttle.

6. WATER RESERVOIR/BAG - 10KG

7. HEAT RATE DISSIPATION TO SPACE 3.8 KILOWATTS

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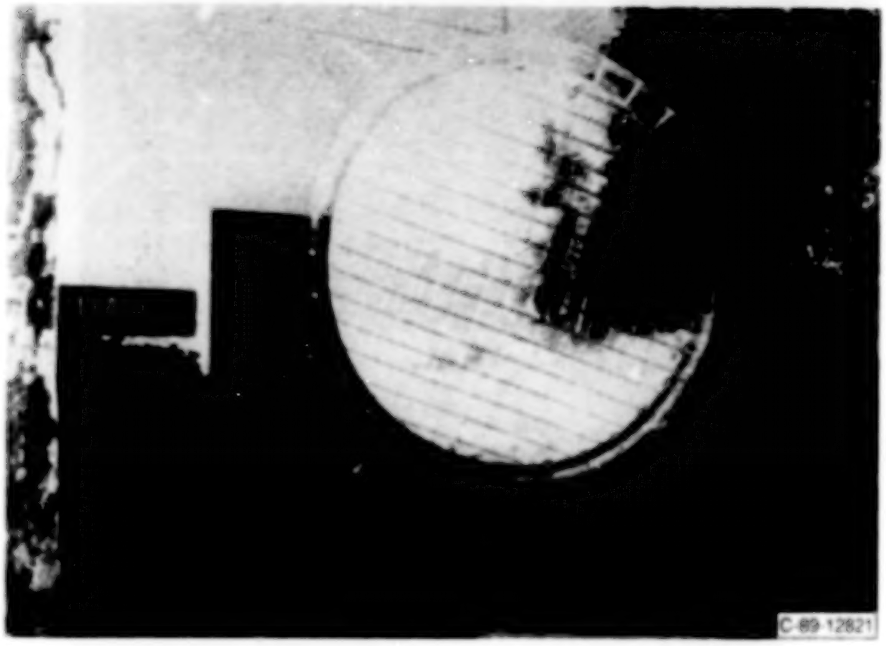
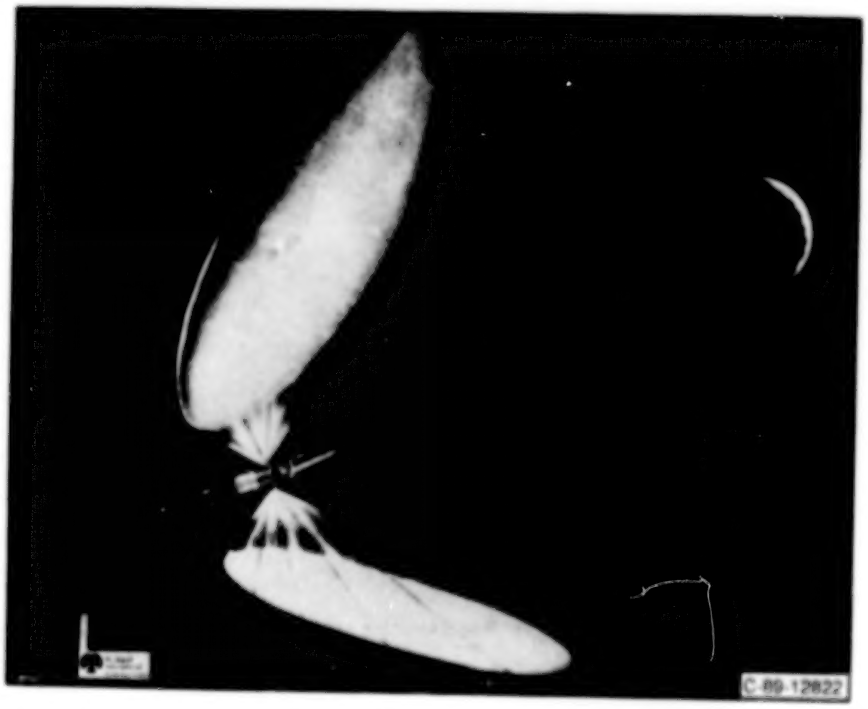
INFLATABLE SPACE TARGET



SOLAR THERMAL ROCKET



SOLAR THERMAL ROCKET - L'GARDE DESIGN

INFLATED REFLECTOR CONCEPT

NASA INFLATED THIN-FILM SATELLITES

SYSTEM	WT (LB)	DIA (FT)	LAUNCH DATE	LIFE (YEARS)	PURPOSE	FILM/METAL THICKNESS (MIL)
ECHO I	135	100	AUG 1960	5	COMM.	0.5 FILM/VDA
EXPLORER IX	34	12	FEB 1961	3	HI-ALT. DENSITY	.5 FILM (2) .5 AL (2)
EXPLORER XIX	34	12	DEC 1963	2	HI-ALT. DENSITY	.5 FILM (2) .5 AL (2)
ECHO II	580	135	JAN 1964	-	COMM.	.35 FILM .18 AL (2)
PAGEOS I	149	100	JUNE 1966	5	EARTH SURVEY	.5 FILM VDA (2000 Å)

ADVANTAGES OF INFLATABLE REFLECTOR

CONFIGURATION
- SUPPORTED AT POWER UNIT
- RADIATOR CLOSE TO POWER UNIT

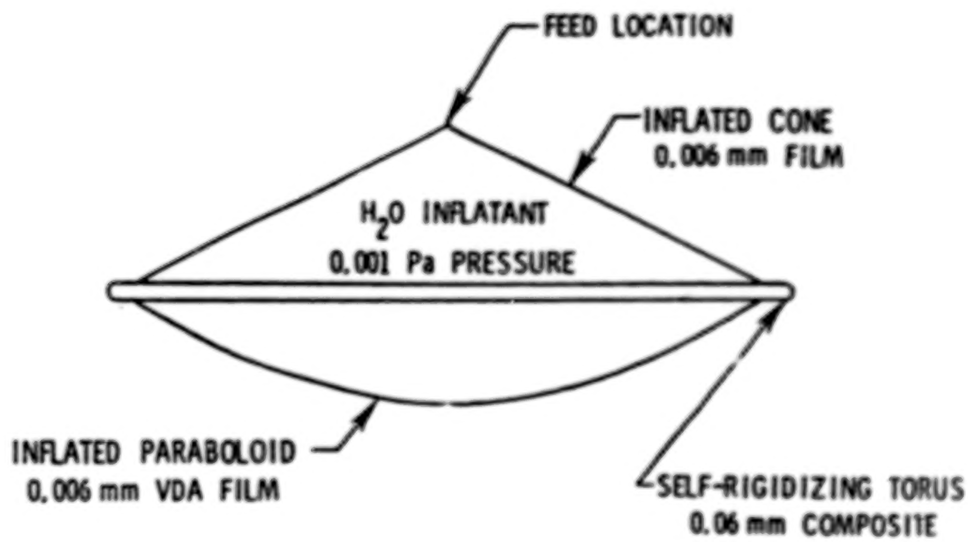
DYNAMICS
- MASS CONCENTRATED AT GIMBAL
- GOOD DAMPING OF MOTION
- GENERALLY NOT SIMPLE HARMONIC MOTION

RELIABILITY
- TOTAL INFLATABLE PACKAGE EASILY REPLACED
- INFLATABLES HAVE SPACE EXPERIENCE
- GROUND TESTABLE

PRACTICALITY
- LOW WEIGHT AND VOLUME
- LOW ENGINEERING/MANUFACTURING COST
- DEVELOPMENT ALREADY STARTED
- EVA MINIMIZED

PERFORMANCE
- INCREASING INTERCEPT AREA IS MINOR CHANGE
- TUNING POSSIBLE THRU PRESSURE ADJSTMT.

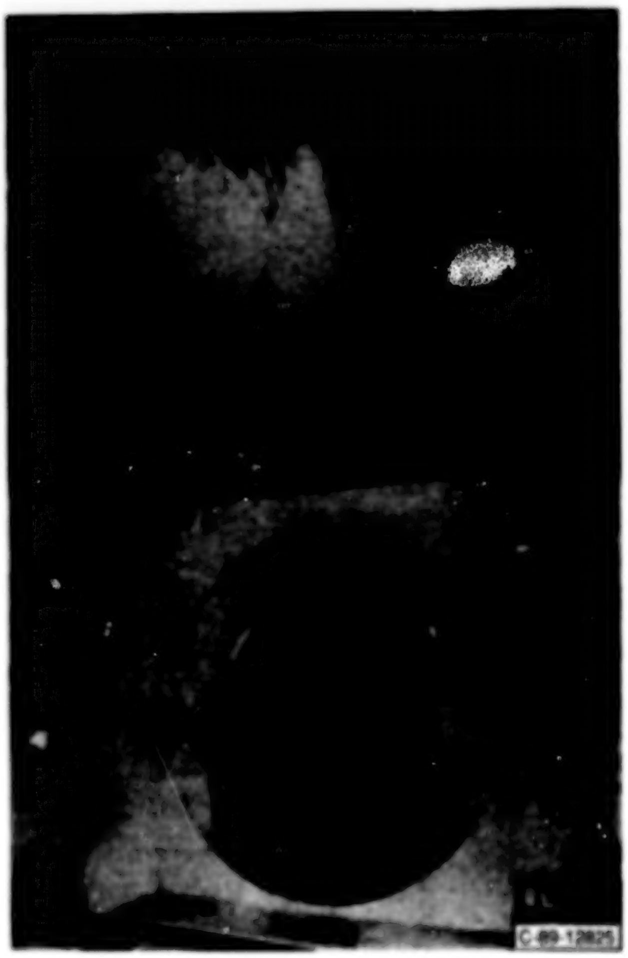
ANTENNA CONFIGURATION



NEAR TERM APPLICATIONS FOR LARGE INFLATABLE ANTENNAS

Agency	System	Comments
U. S. State Department	Voice of America	700 ft. dia., 26 MHz
NASA	Ground Mobile	200 ft. dia., 850 MHz
U. S. Navy	Integrated Tactical Surveillance System	Synchronous Version, 200 ft. dia.
U. S. Air Force	Space Radar mm-wave Radiometer Solar Concentrator "Dark" Programs	Phased Arrays Prime Candidate 10-30m, better accuracy needed Solar Rocket 50-250 ft. dia.

3 - METER INFLATED REFLECTOR - UNINFLATED CONDITION, DEVELOPED FOR NASA LANGLEY



3 - METER INFLATED REFLECTOR - INFLATED CONDITION

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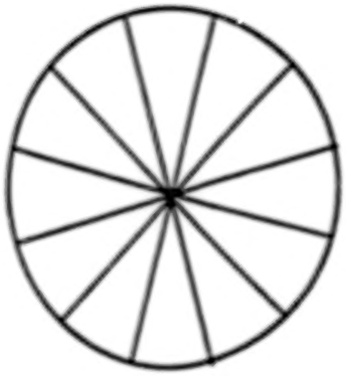
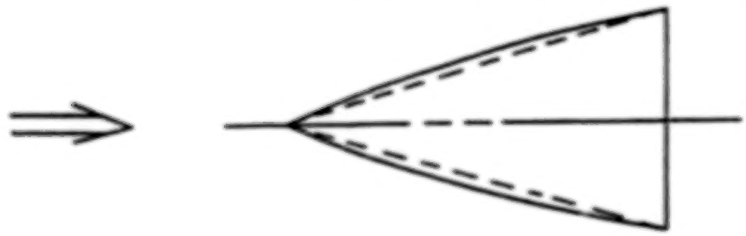
GORE DESIGN

DETERMINE SHAPES OF THE GORES THAT WILL FORM A PARABOLIC DISH UPON INFLATION



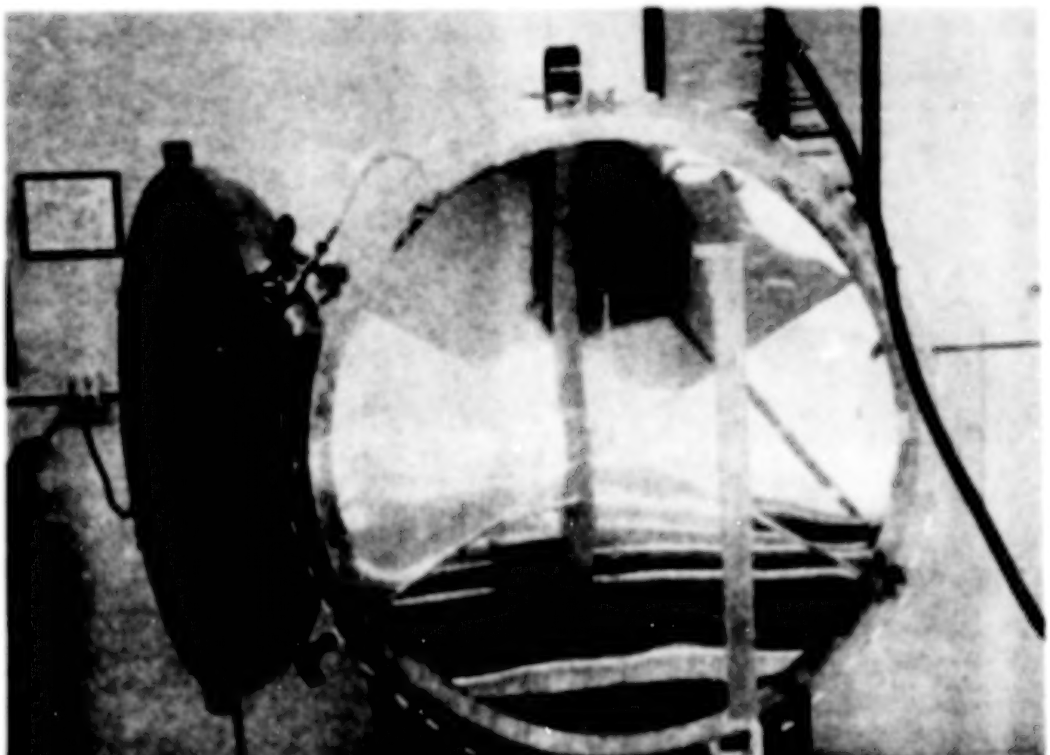
ON-AXIS REFLECTOR



"FATTER" THAN A TRIANGULAR WEDGE

** USE FLATE CODE **

ONE M ONE METER DIAMETER INFLATED REFLECTOR DEVELOPED FOR THE[B] AF ROCKET PROPULSION LAB



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3-Meter-Diameter Test Paraboloid
(HAIR Program)

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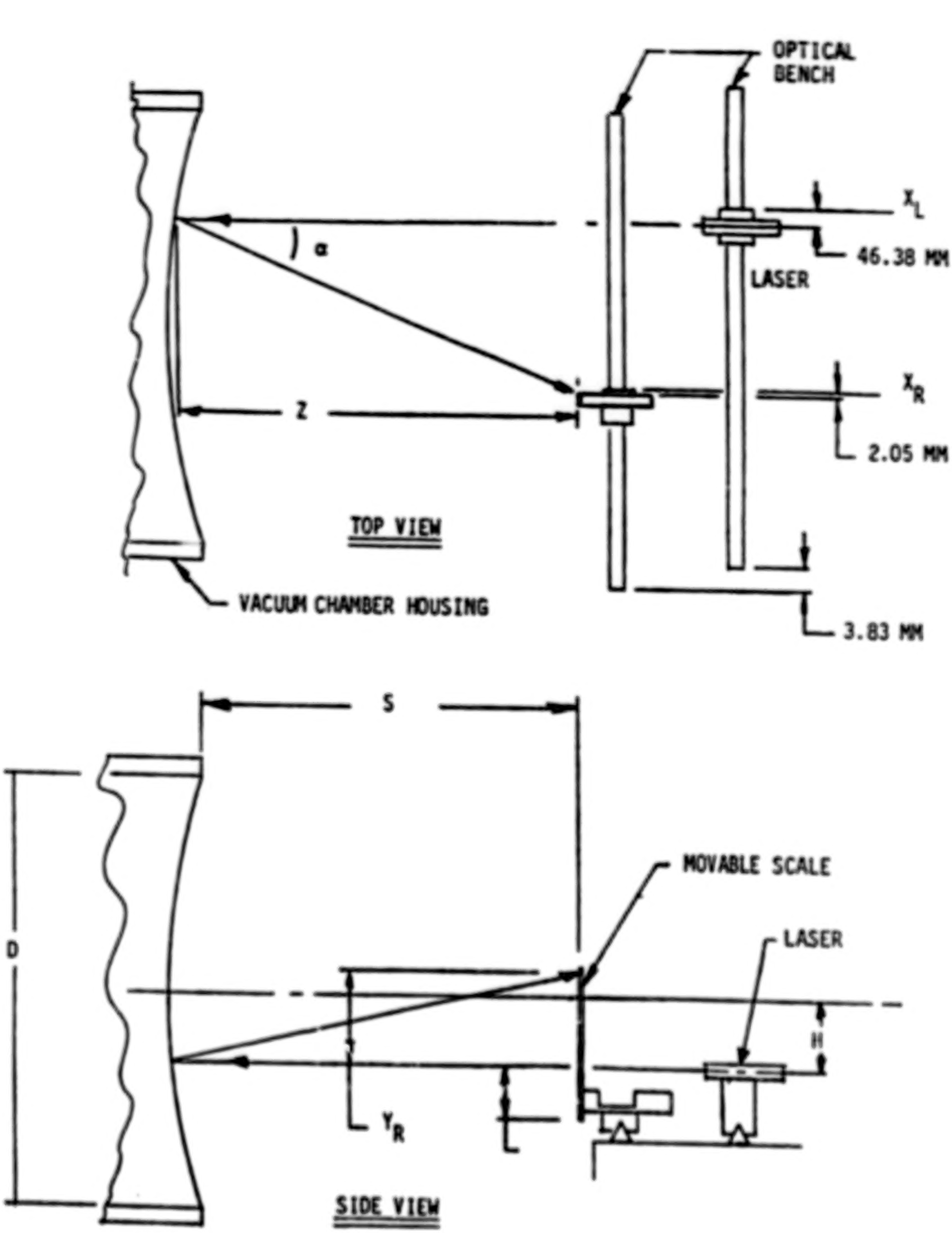
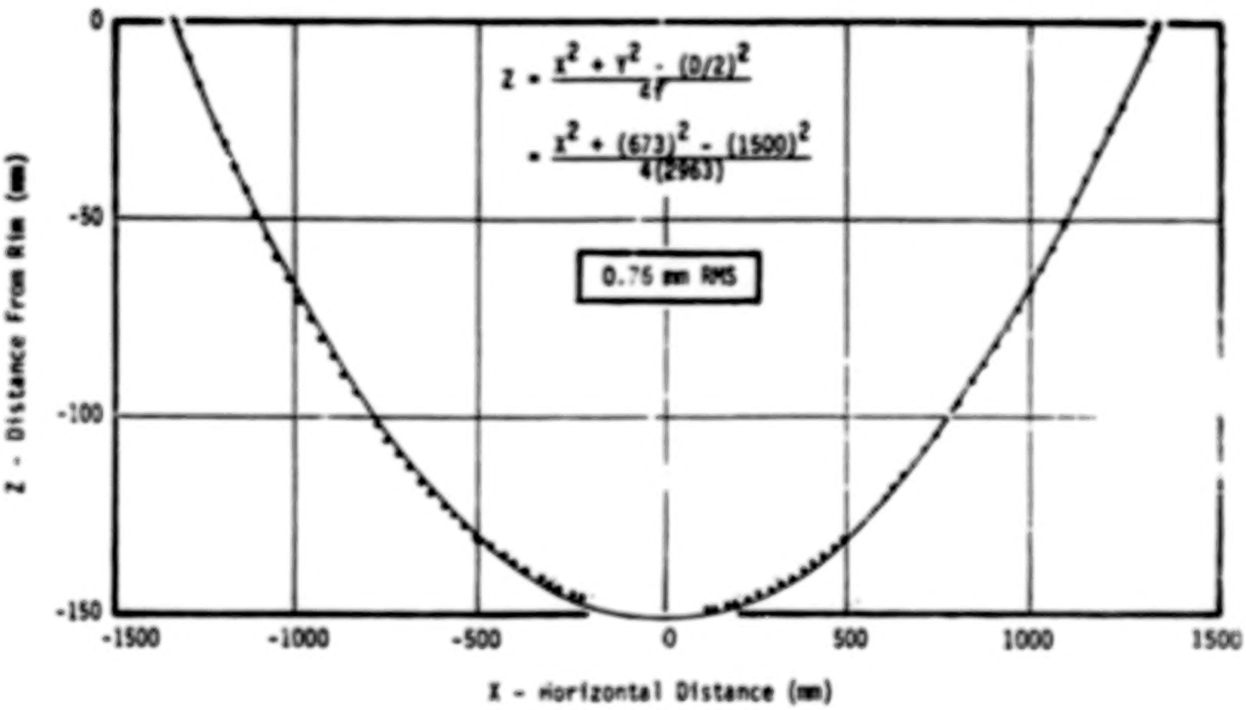


SLOPE-MEASUREMENT OPTICAL SETUP

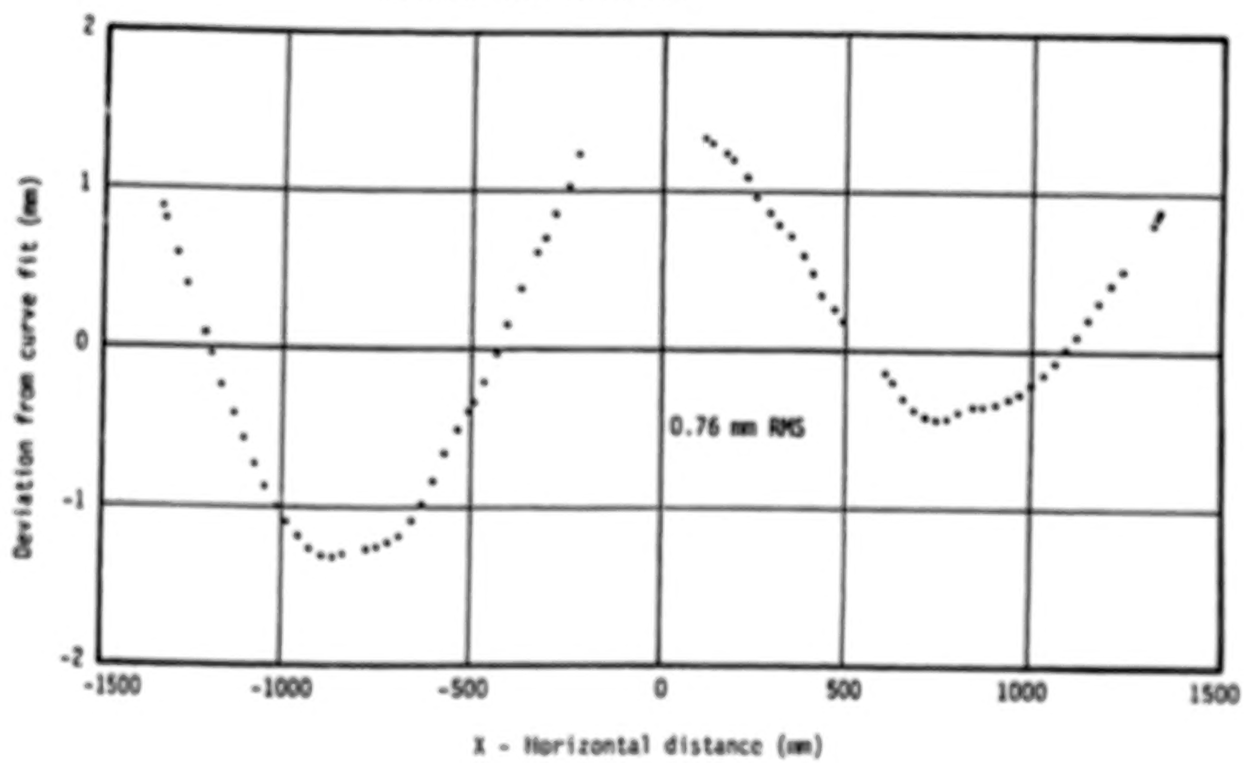
MEASUREMENT OF PARABOLOID SURFACE ACCURACY

32 ½-mil VDA Mylar Gores
½-mil Mylar Tape

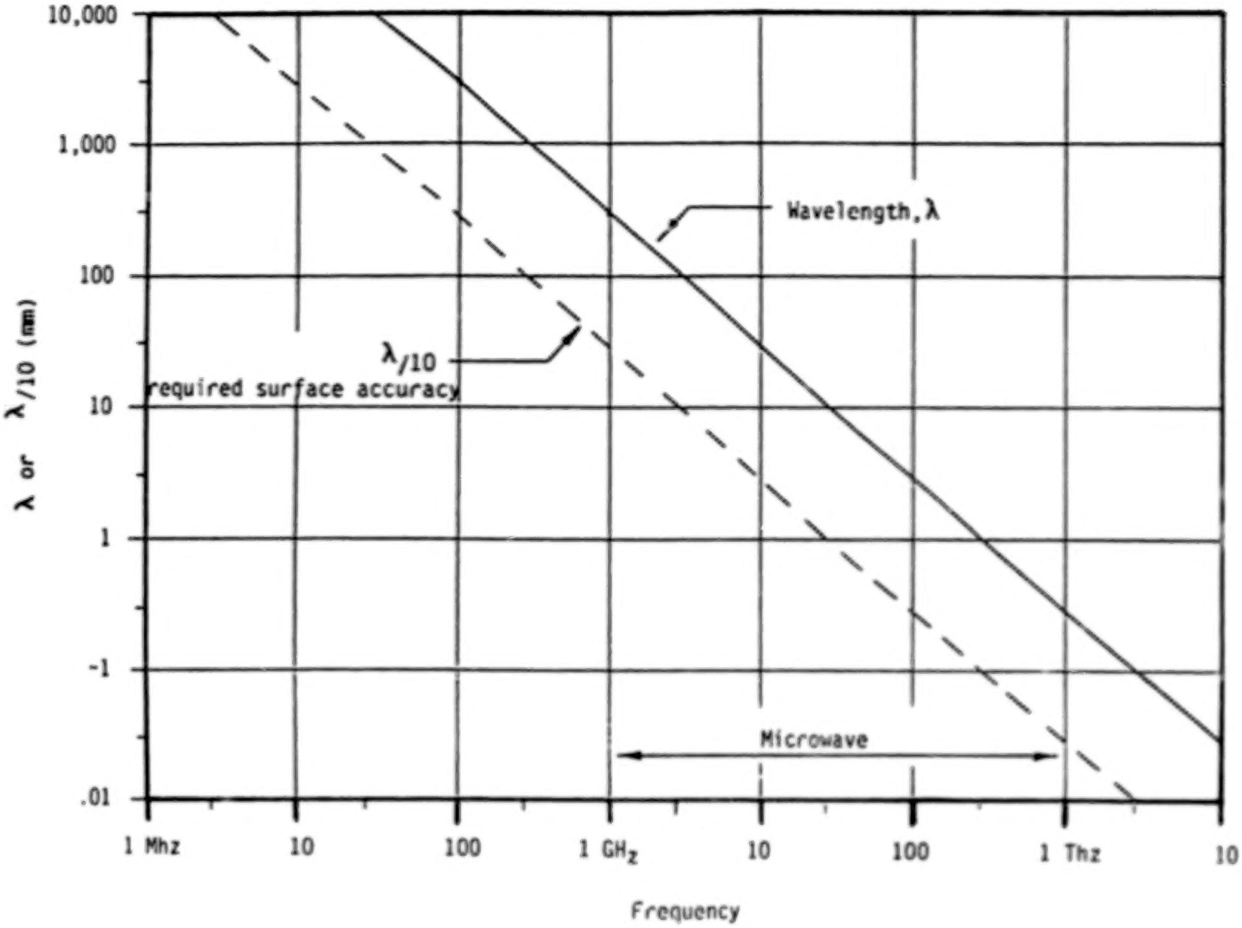
3 Meter Diameter
Measured 673 mm Below Centerline



MEASUREMENT OF PARABOLOID

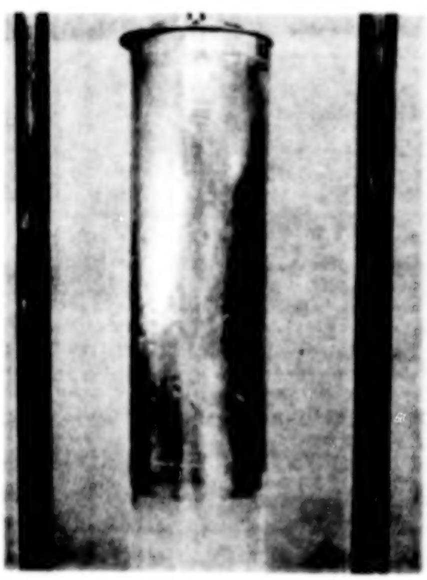


REQUIRED ANTENNA ACCURACY

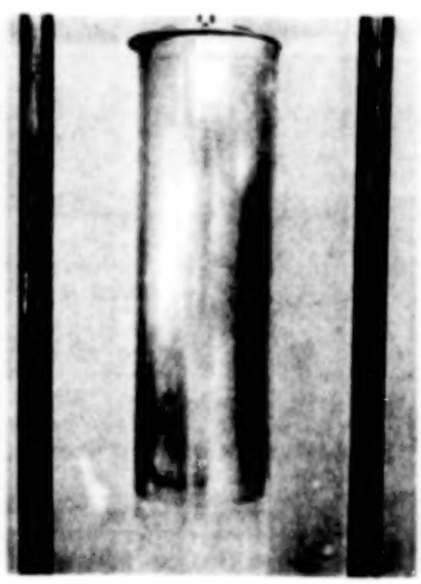


<u>CYLINDER TESTS</u>

THESE RIGIDIZED CYLINDERS WILL FORM THE TORUS OF THE INFLATED ANTENNA.



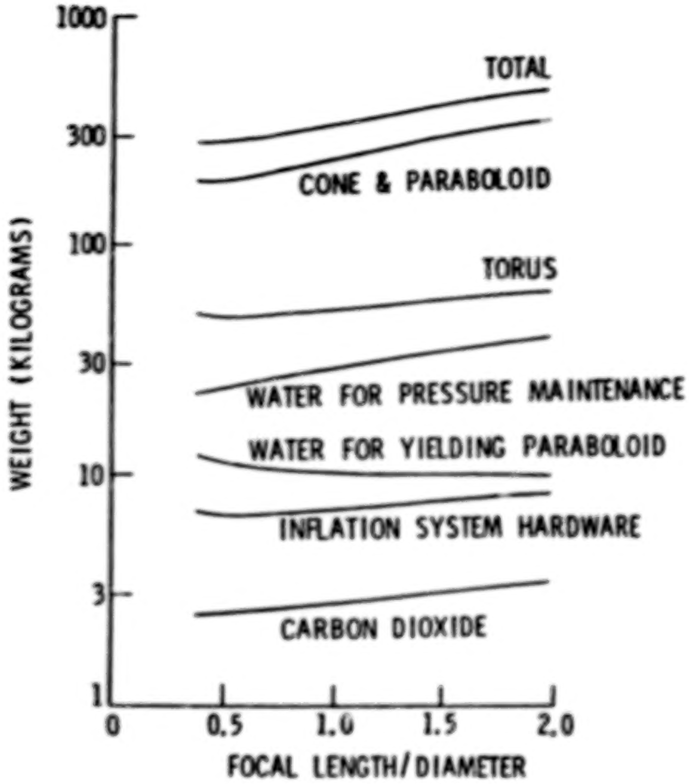
BEFORE PRESSURE



AFTER PSIG

AFTER 49.5 LBS FORCE COMPRESSIVE

WEIGHT BREAKDOWN FOR 100-METER DIAMETER REFLECTOR



PROGRAM PLAN

1. <u>1.0 mm accuracy</u>

   - have demonstrated this for NASA and AFAL
   - need to incorporate torus
   - 1.5 years to build 10 meter flight reflector
   - roughly \$2 to \$3 million

2. <u>0.1 mm accuracy</u>

   - best tests have yielded 0.1 mm
   - need higher pressures, heavier torus
   - 3 meter testing
   - three years to build 10 meter flight reflector
   - roughly \$5 million

N90
2/800
UNCLAS

FREE ELECTRON LASERS DRIVEN BY LINEAR INDUCTION ACCELERATORS - HIGH POWER RADIATION SOURCES

T.J. Orzechowski
Lawrence Livermore National Laboratory
Livermore, California 94550

This talk will address the technology of FELs and LIAs

- Fundamentals of FELs
- Basic concepts of linear induction accelerators
- The Electron Laser Facility — a microwave FEL
- PALADIN — an infrared FEL
- Magnetic switching
- 'IMP'
- Future directions — relativistic klystron

The Free Electron Laser under development at LLNL is based on a single pass amplifier design

- The electron beam is generated by a Linear Induction Accelerator:

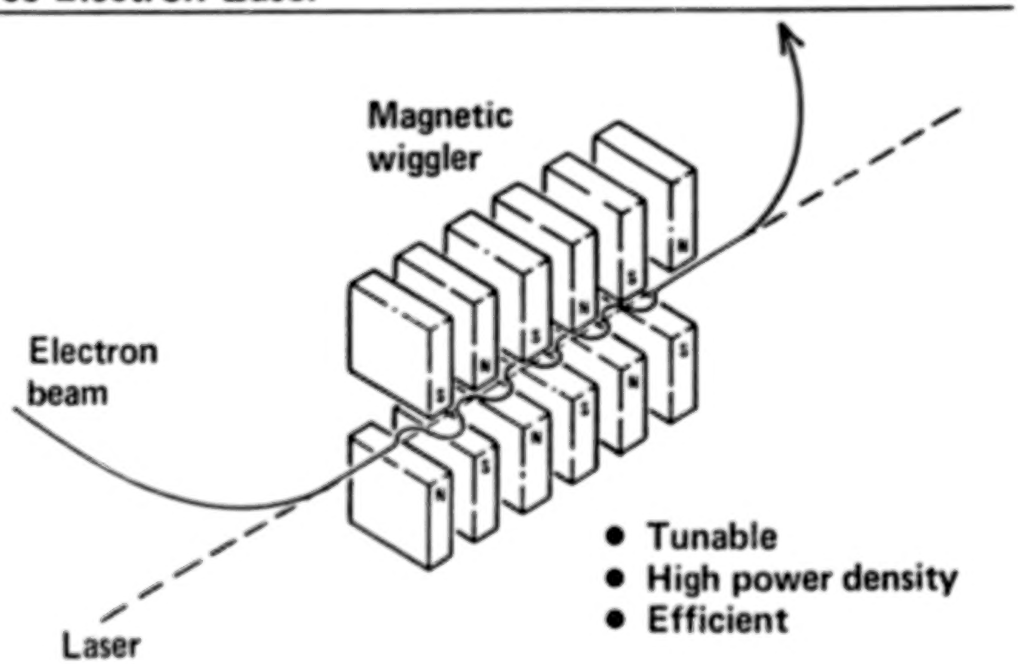
$E_b \approx$ several MeV
$I_b \approx$ few kA
$P_b \approx 10^{10}$ W

$\tau_p \approx 50$ nsec
prf $\approx$ few kHz
duty factory $\approx 10^{-4}$
$P_b \approx 10^6$ W

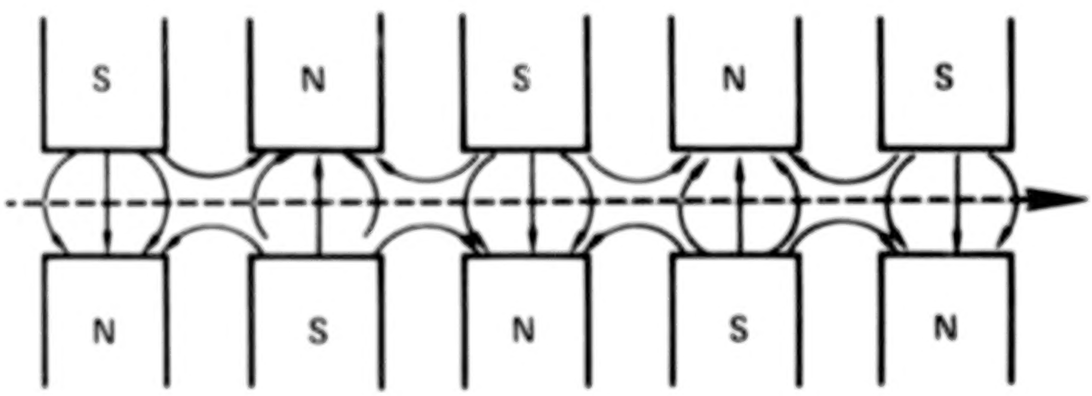
- In the FEL amplifier, an injected signal grows exponentially, trapping a significant fraction of the electron beam. Proper design of the wiggler fields leads to a large fraction of the beam energy being converted to radiation energy ($\approx$ 40%)

A free-electron laser converts the kinetic energy of a relativistic electron beam into coherent radiation. The electrons are given transverse momentum in a device called a wiggler. This transverse momentum can now couple to the transverse electric field of a co-propagating electromagnetic wave.

Free Electron Laser



The wiggler-a periodic, vertical magnetic field



---- Electron beam

——— Magnetic field lines

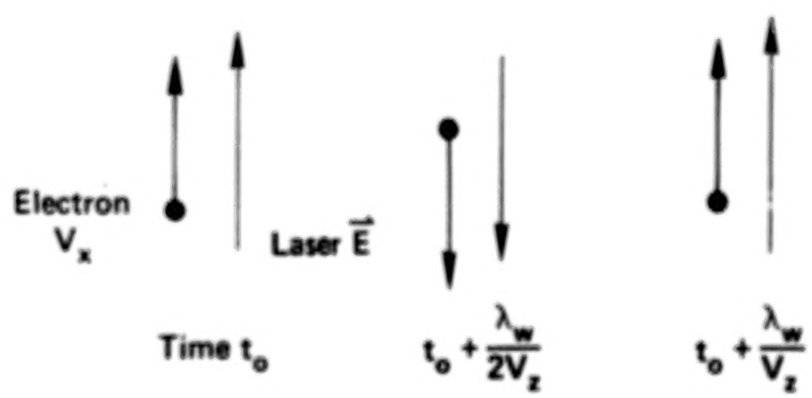
On midplane $\vec{B} = B_{yo} \cos k_w z \quad k_w = 2\pi/\lambda_w$

In resonance, the electromagnetic wave travels one wiggler period plus one radiation wavelength in the time the electron has traveled one wiggler period. This "slippage" keeps the electron's transverse velocity always in the same direction as the electronic field of the radiation. Thus

$$\int v_\perp \cdot E_{rf}\, dz \neq 0 \quad .$$

Electron-laser coupling

- **Moving with the average motion of an electron**



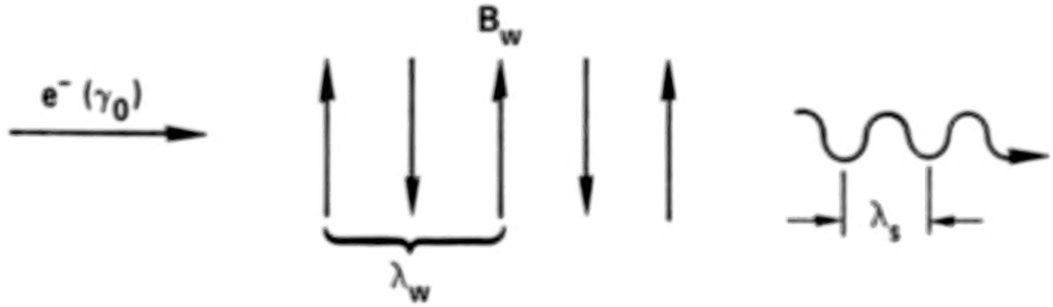
- **$\vec{V} \cdot \vec{E}$ always greater than zero ⇒ steady energy <u>loss</u> of electron ⇒ steady energy <u>gain</u> of laser**

The resonance condition depends on the beam energy

$$\gamma \equiv 1 + \frac{eV}{mc^2} \quad .$$

λ_w (wiggler period) and B_w (wiggler magnetic field).

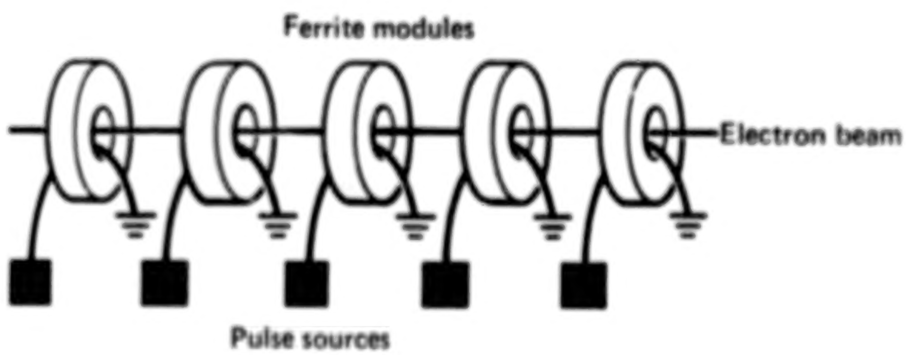
Wavelength scaling



The output frequency of the FEL is the result of a Lorentz contraction (of the wiggler period) followed by a Doppler shift.

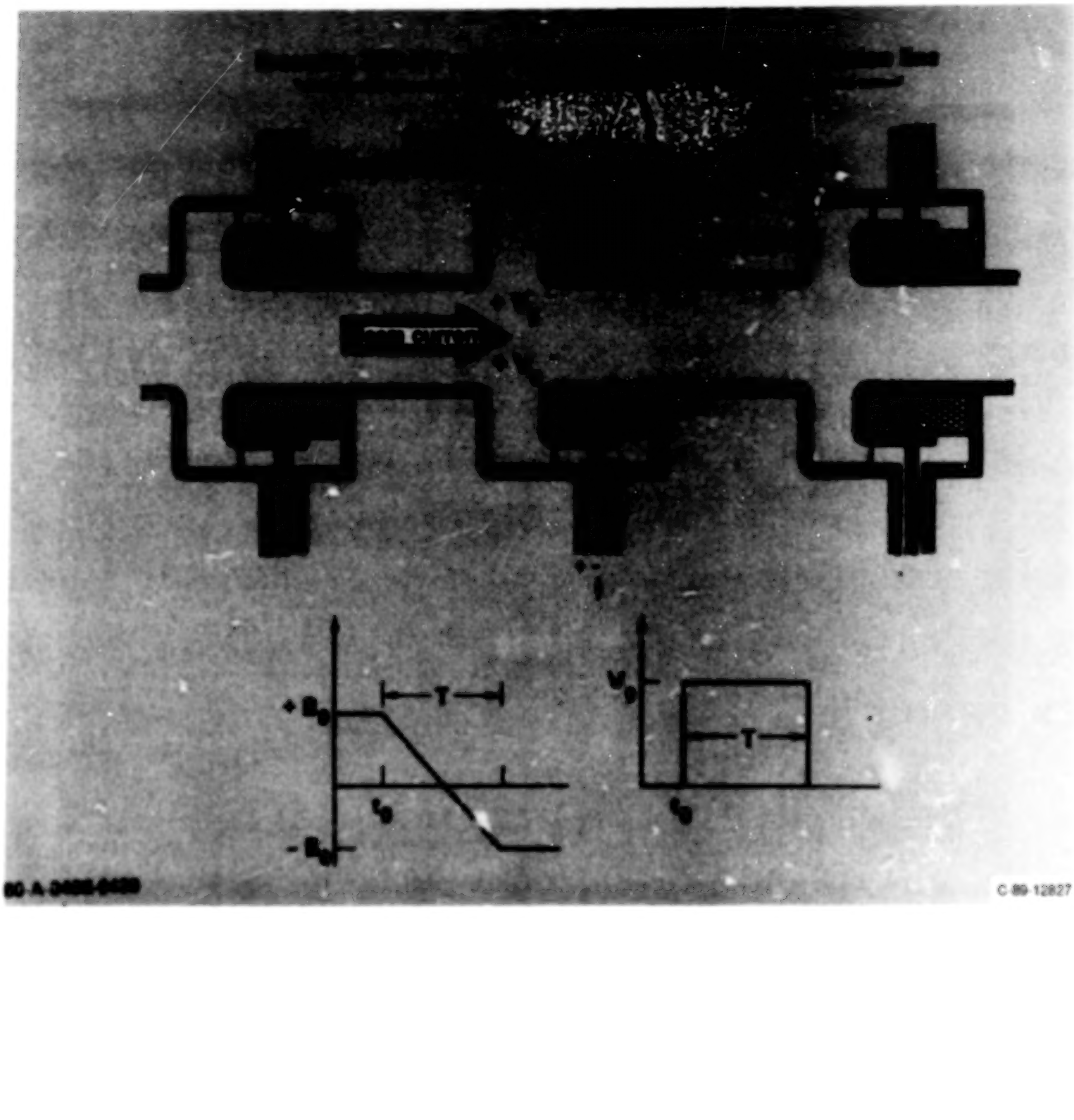
$$\lambda_s = \frac{\lambda_w}{2\,\gamma_{\parallel}^2} = \frac{\lambda_w}{2\,\gamma_0^2}\left[1 + \frac{1}{2}\left(\frac{e\,B_w\,\lambda_w}{2\,\pi mc}\right)^2\right]$$

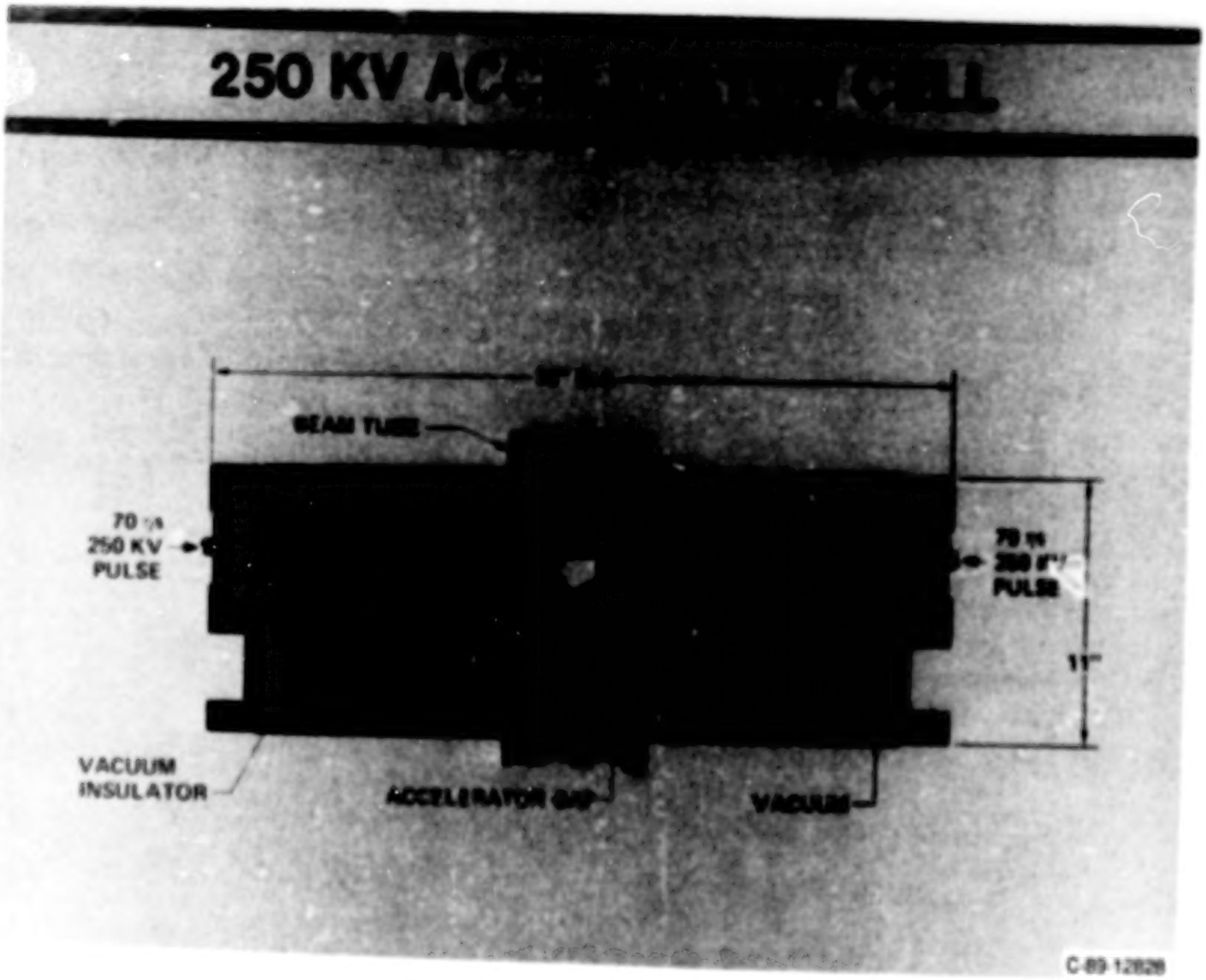
LIA concept



- An induction linac works as a series of 1:1 pulse transformers threaded by the electron beam
- Each module generates an increment of beam acceleration

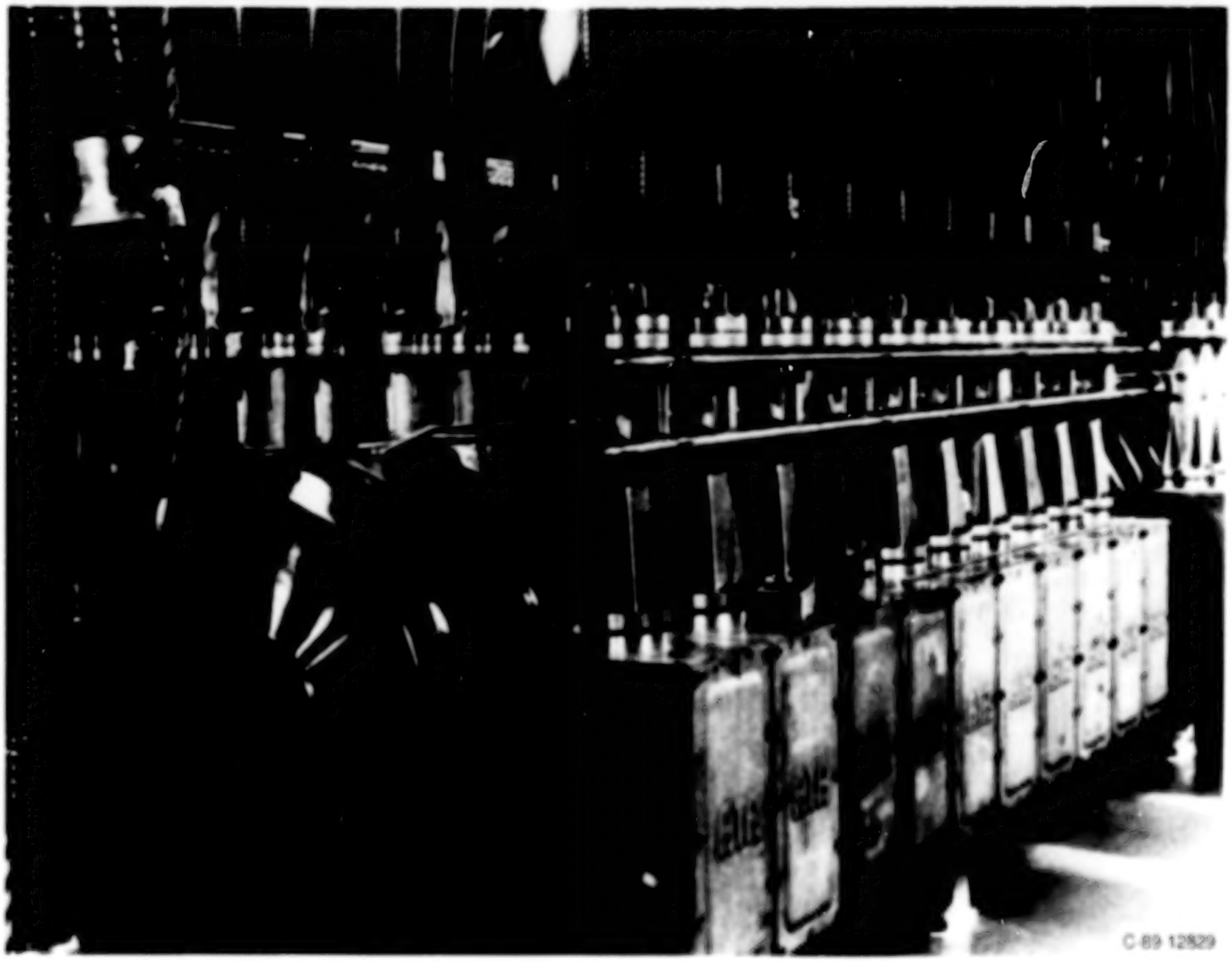
The accelerating voltage is impressed across the accelerating gap. The accelerating voltage and pulse length are determined by the amount of ferrite (volts-seconds) in the accelerator cell.




250 KV
BEAM TUBE
250 KV
PULSE
11"
VACUUM
INSULATOR
ACCELERATOR GAP
VACUUM

C-89-12828

Picture of 2.5-MeV (ten cells) section of ATA. The ten-cell block is about 3-meters long.



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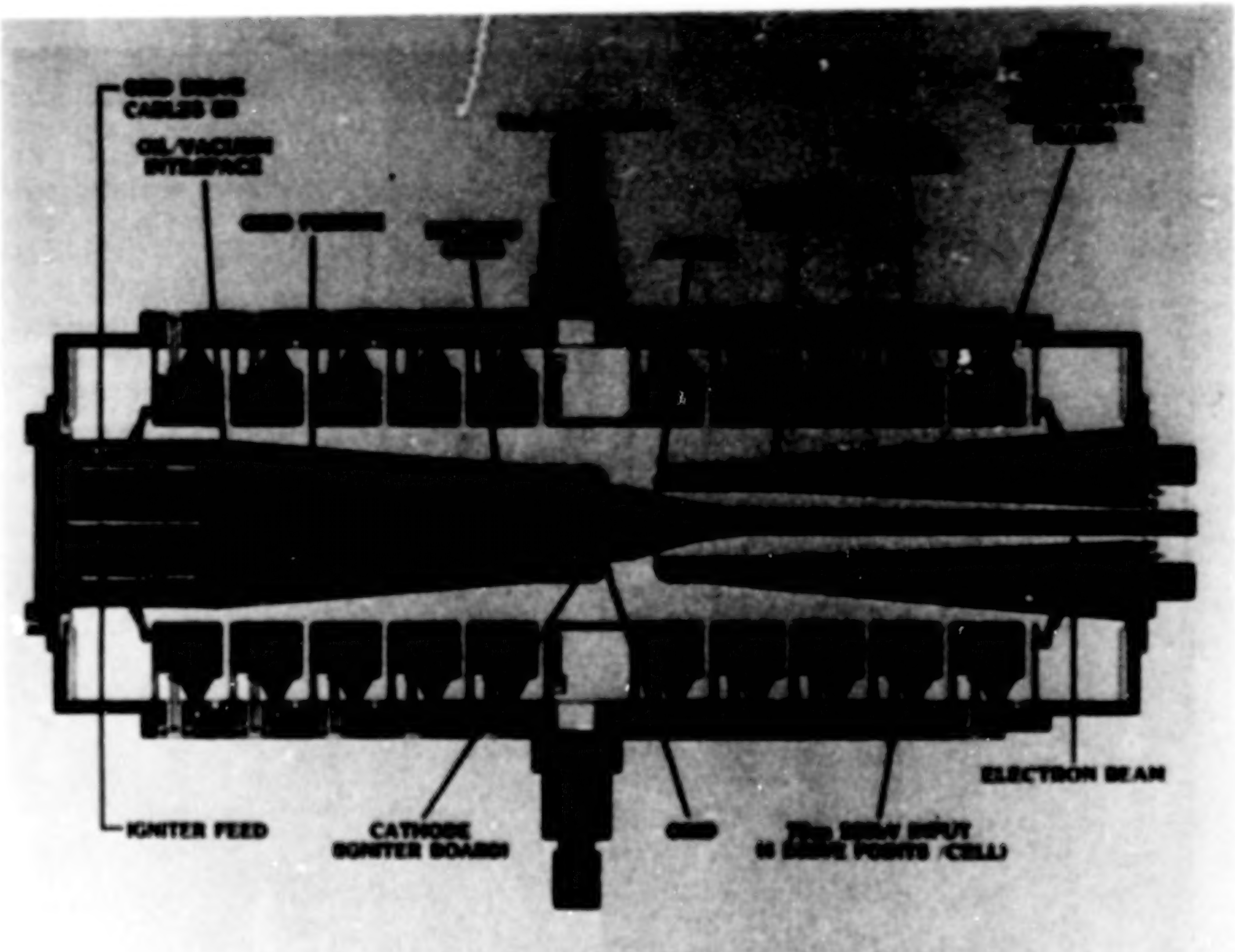
The source of the electron beam, called an injector or gun, is a diode driven by ten inductive cells connected in series.



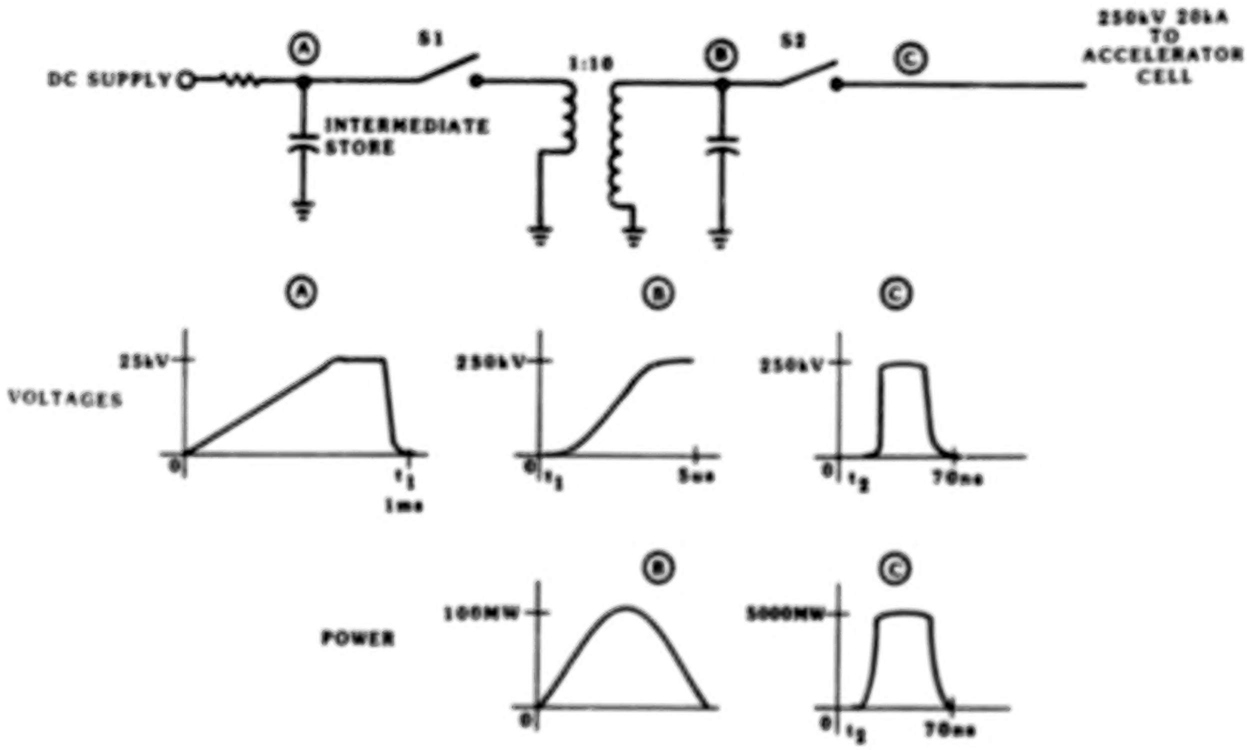
ATA 2.5MeV ELECTRON INJECTOR

Conventional pulse drive for induction linacs.

S_1 = thyratron

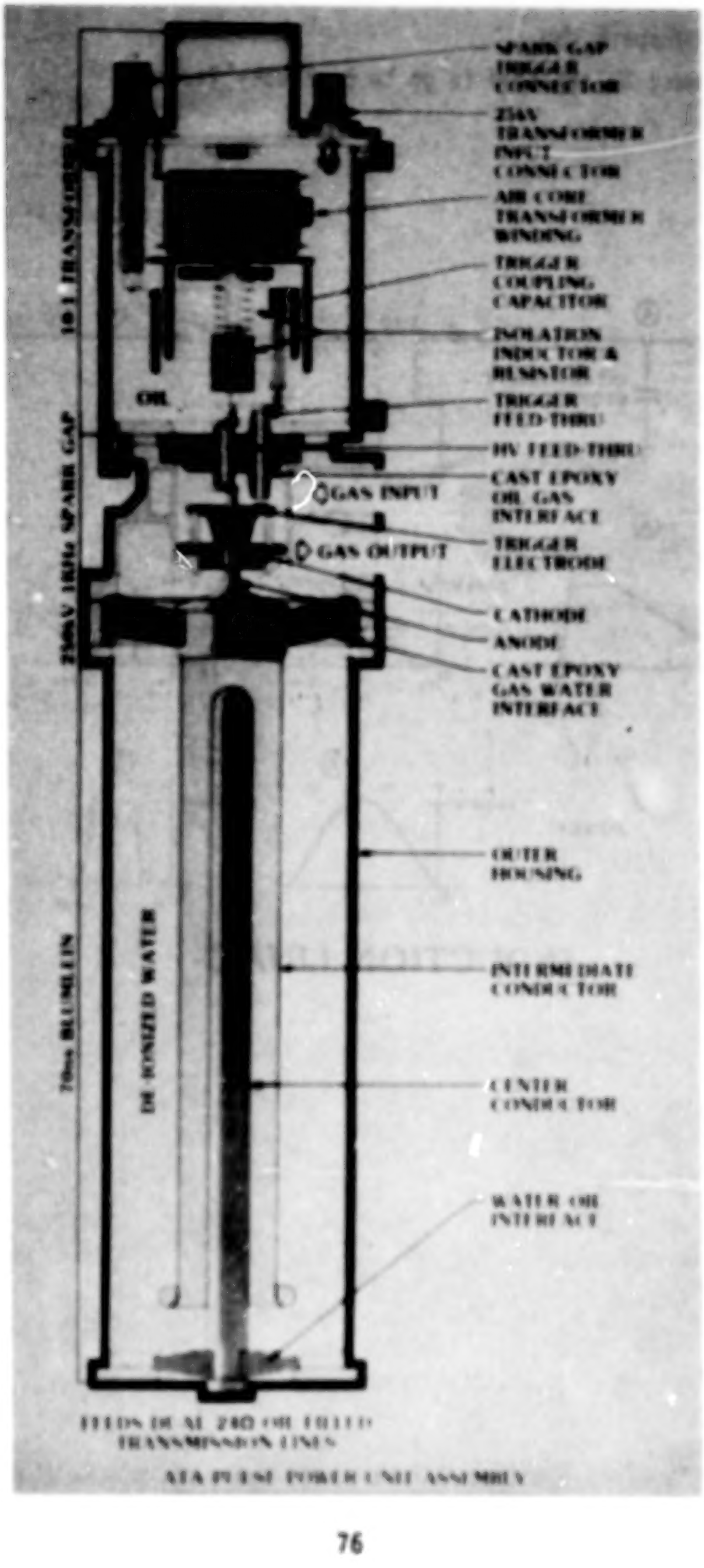
S_2 = pressurized spark gap

The spark gap must be replaced to go to high duty factor.



INDUCTION LINAC

Schematic of conventional pulsed power unit.



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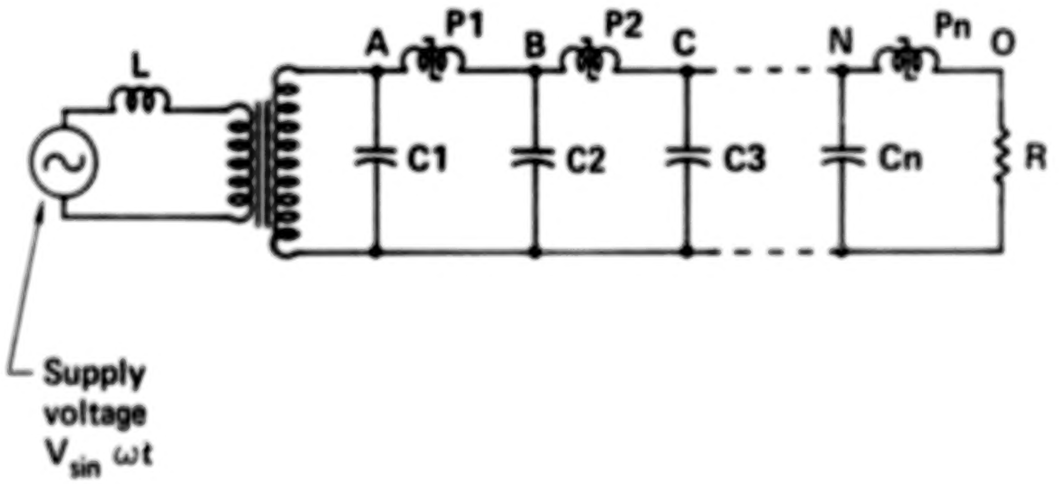
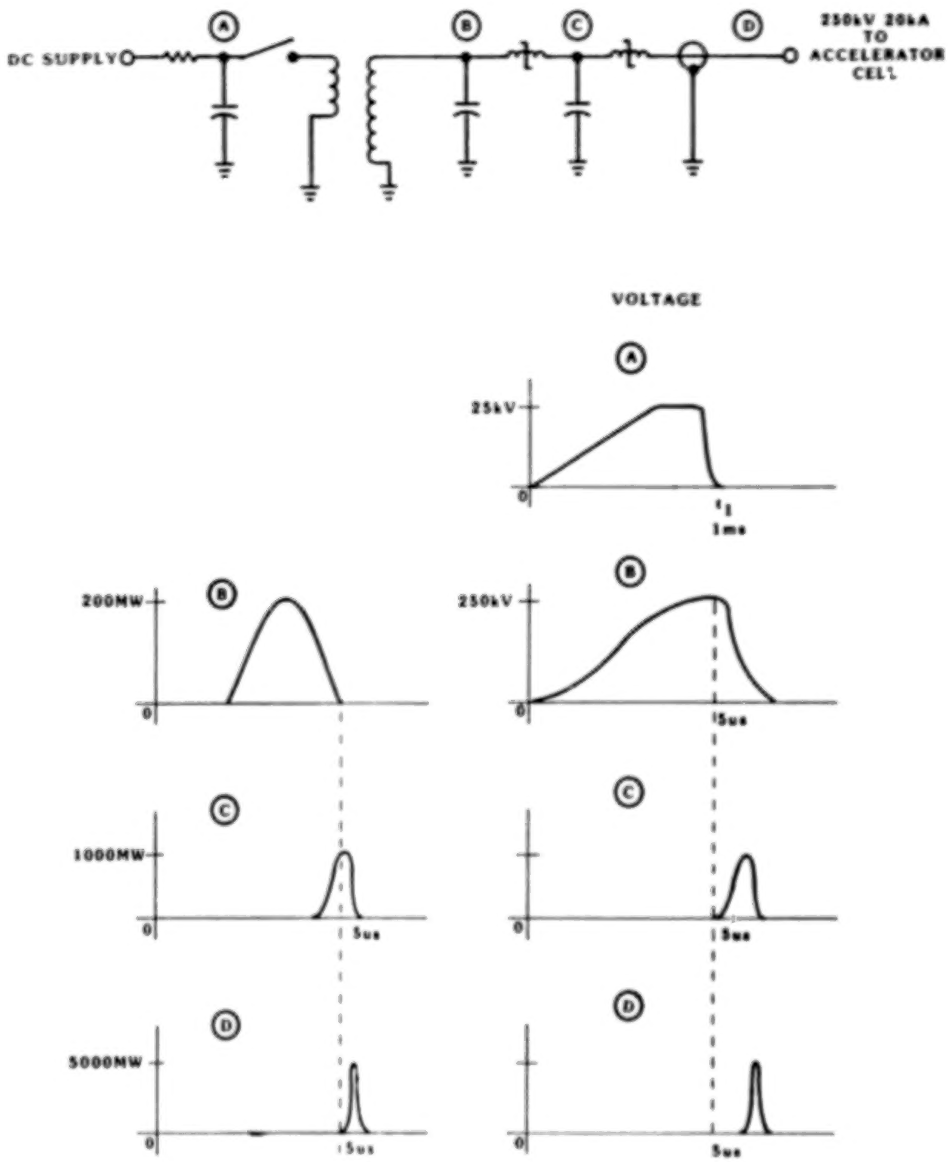
Magnetic pulse compressor concept. P_1, P_2... are saturable reactors. During the initial charge phase of C_n, P_n is a high-impedance shunt with only a small leakage current passing through it. When it saturates, it is a low impedance path and C_n dumps into C_{n+1}. Proper design of the circuit results in pulse compression.

Simplified schematic of a magnetic pulse compressor



Induction linac drive based on saturable reactors.



INDUCTION LINAC NONLINEAR MAGNETIC DRIVE

The Electron Laser Facility (ELF) serves a threefold purpose:

1. Study basic physics of Free Electron Lasers
2. Serve as a test bed for the physical models used in the design of other FEL amplifiers
3. Provide a source of high power microwave radiation

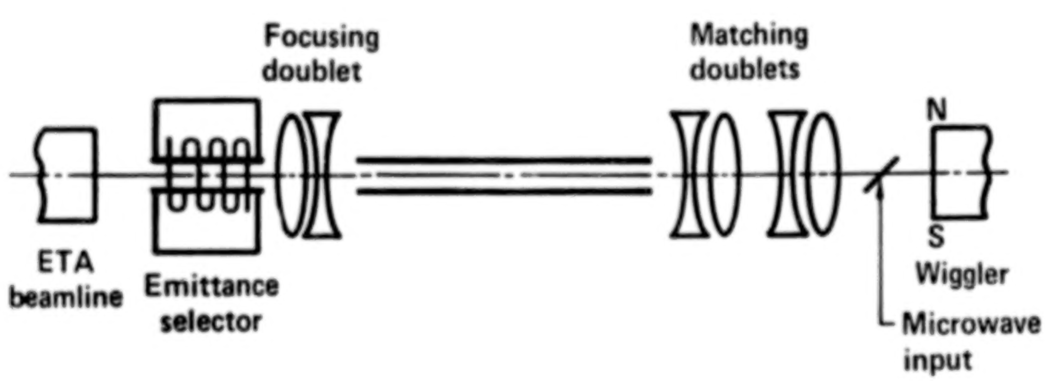
Principal features of ELF

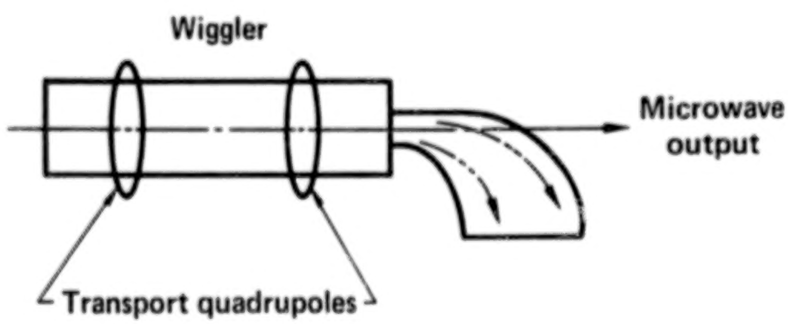
- Operates in an amplifier mode
  - $\lambda_s = 8.6$ mm
  - $P_{in} \leqslant 50$ kw
- Pulsed electromagnetic wiggler
  - $\lambda_w = 9.8$ cm
  - $L_w = 3$ m
  - $B_{w,max} = 5$ kG
  - Linearly polarized
  - No axial magnetic guide field (horizontal focusing provided by external, horizontally focusing quadrupoles)
  - Each two periods independently controlled
- Interaction region
  - Oversized waveguide (3 cm $\times$ 10 cm)
  - Fundamental excitation mode: TE_{01}

Electron beam characteristics

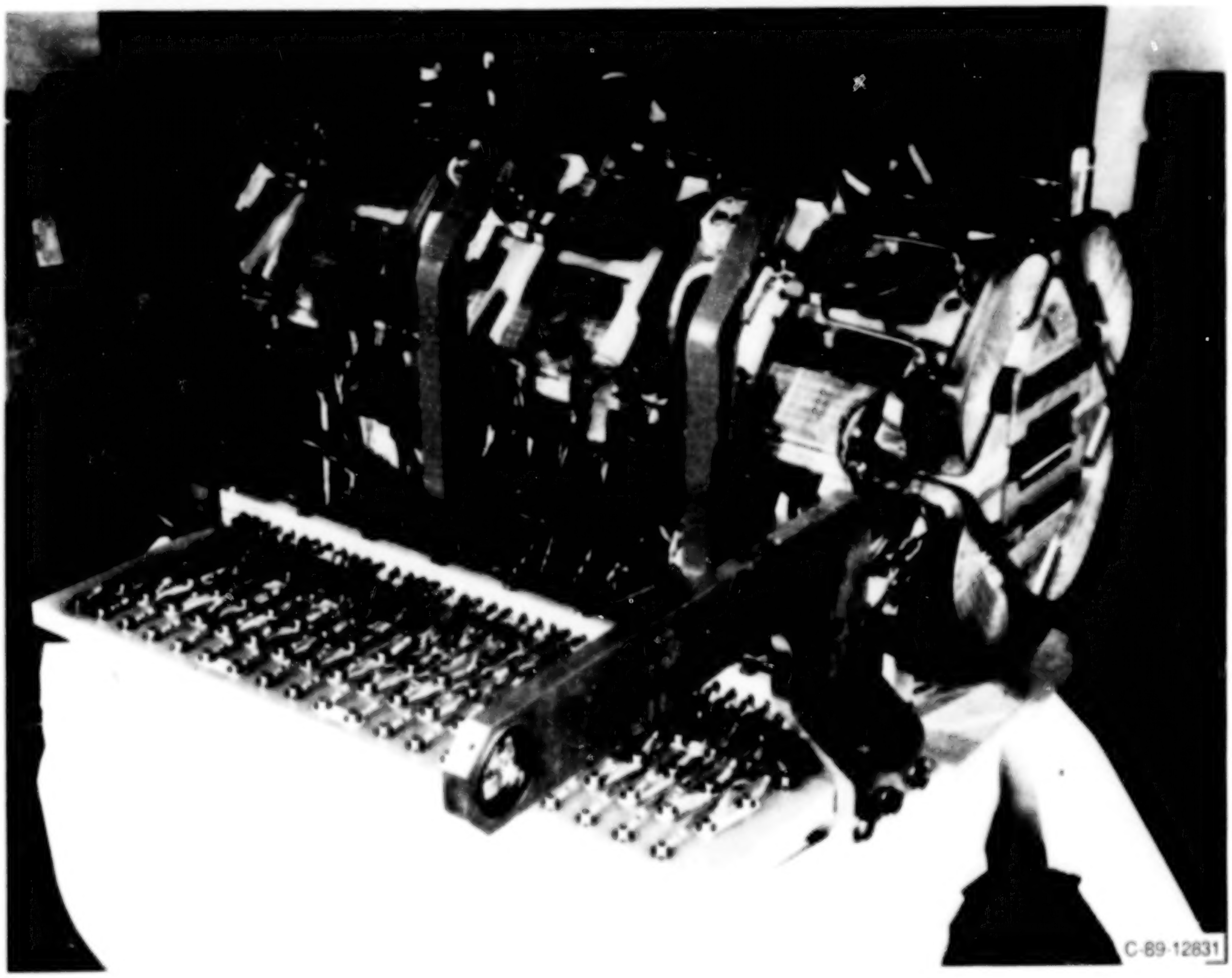
- Beam energy $\simeq$ 3.5 MeV
- Field emission cathode
- 30 ns pulse length
- 1 Hz prf
- ~4 kA accelerated current
- $\mathcal{J} = 2 \times 10^4$ amps/cm^2 -rad^2

ELF Beamline





One-meter section of ELF wiggler.



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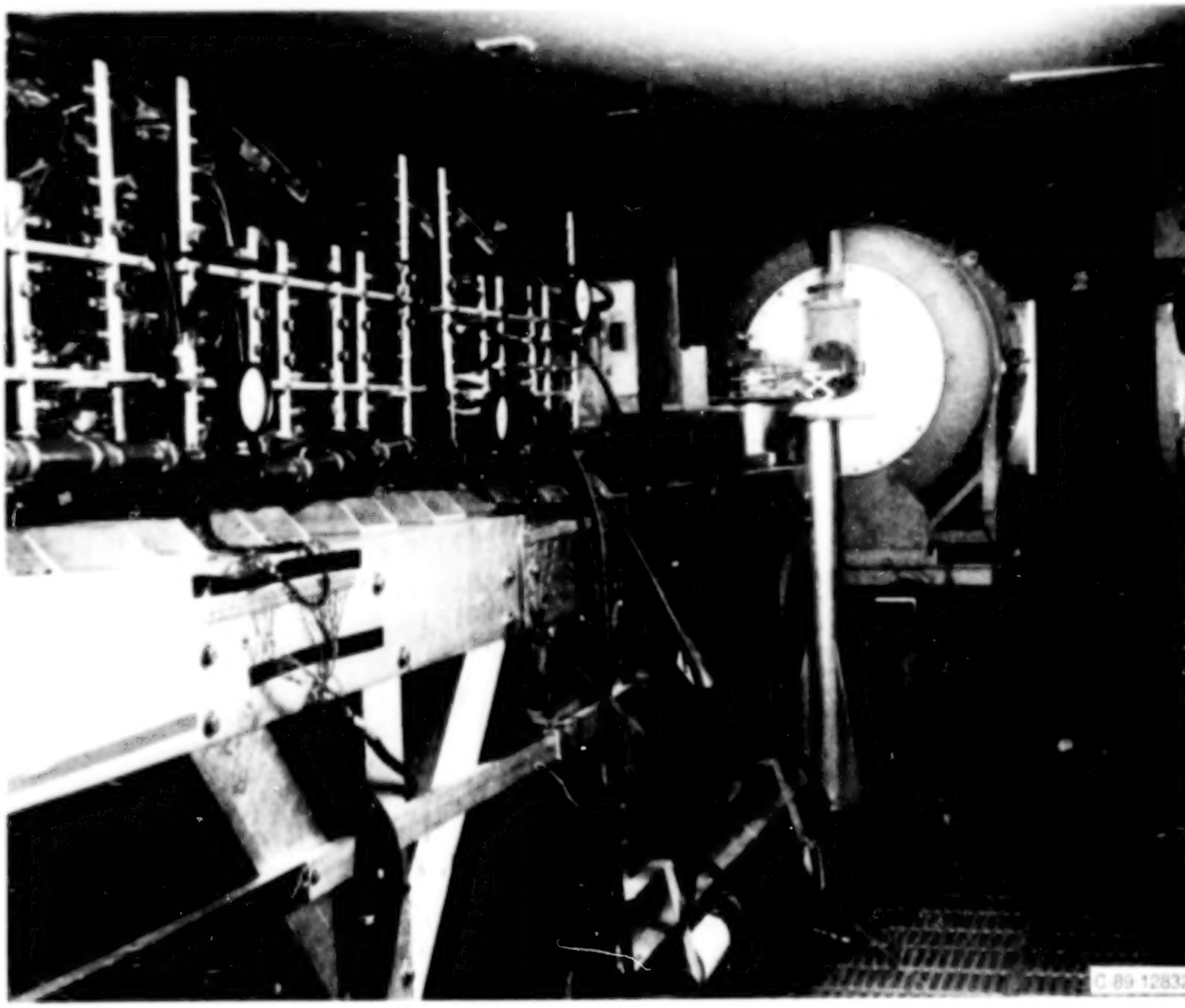
Picture of ELF experiment. On the left is the wiggler magnet. Right of center is a large vacuum diffraction tank which eliminated the problem of air breakdown.



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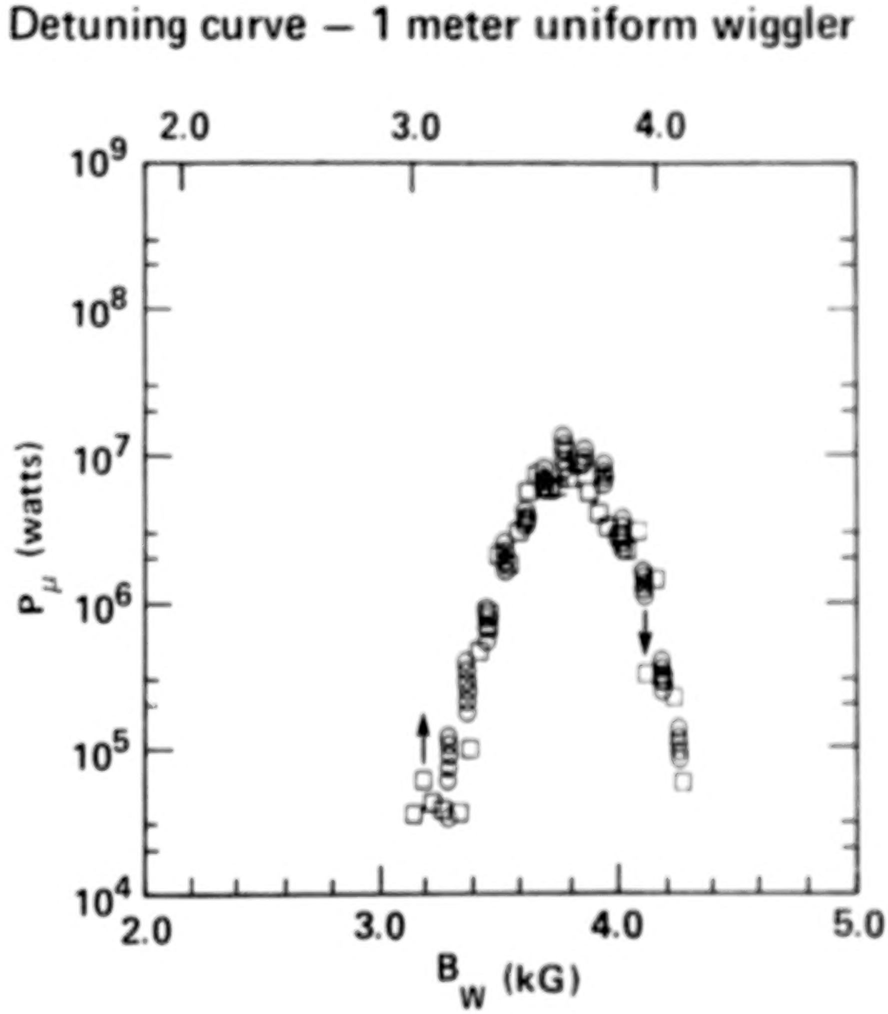
Power output as a function of wiggler magnetic field. Circles are experimental data while squares are the result of numerical simulation.

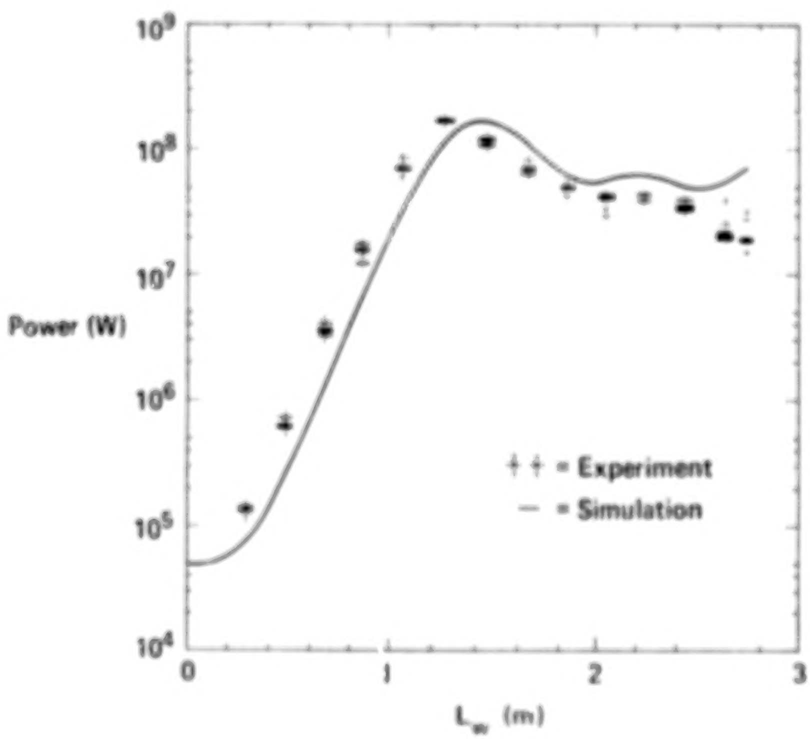


Power output as a function of wiggler length. The device saturates at about 1.2 meters. Sufficient energy (~7%) has gone from e-beam to radiation to violate resonance condition (see "wavelength scaling" viewgraph)

$$\gamma \equiv 1 + \frac{eV}{m_e c^2}$$

where eV is the beam energy, $M_e c^2$ is the electron rest mass energy. The solid line is the result of a numerical simulation.

Microwave power vs wiggler length: uniform wiggler—B_W=3.72 kG



Prescription for tapering the wiggler fields

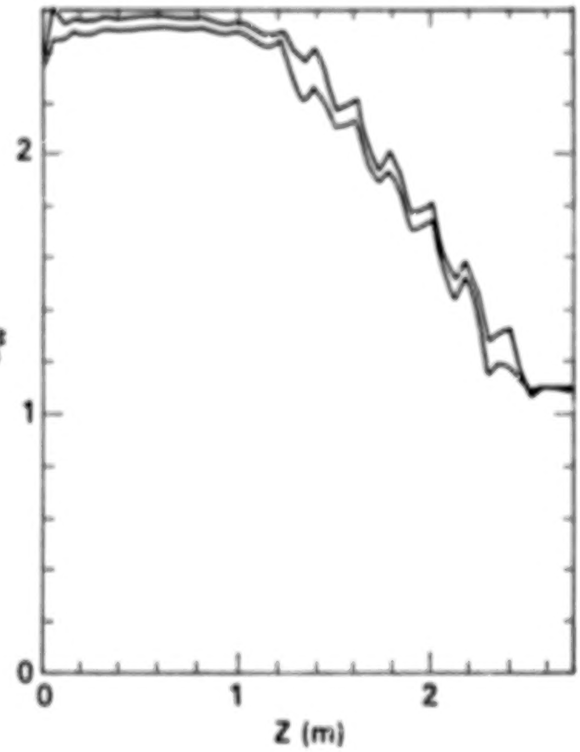
- Use a uniform wiggler on resonance almost out to saturation. Keep the remaining wiggler well below resonance ($B_w = 0.4 \times B_{w,res}$).

- Tune each subsequent power supply (2 period segments) to maximize the output power.

Tapering the wiggler magnet (changing the wiggler magnetic field and/or period) allows the resonance condition to be maintained throughout the length of the device.

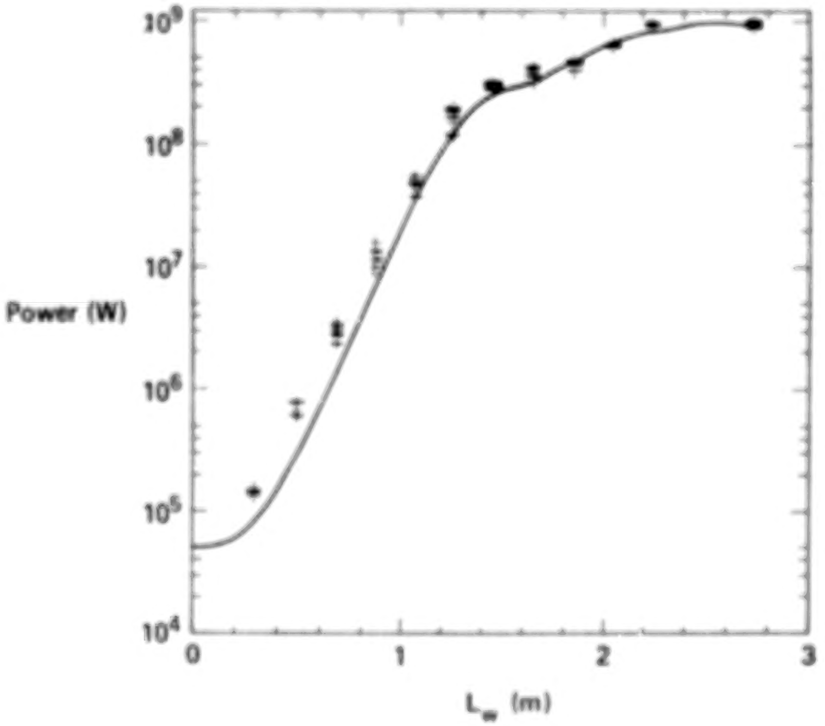
$$a_w = \frac{eB_w\lambda_w}{\sqrt{8}\ \pi\ m_e c} \qquad \text{(in MKS units)}$$

Optimized tapered wiggler field (computed)



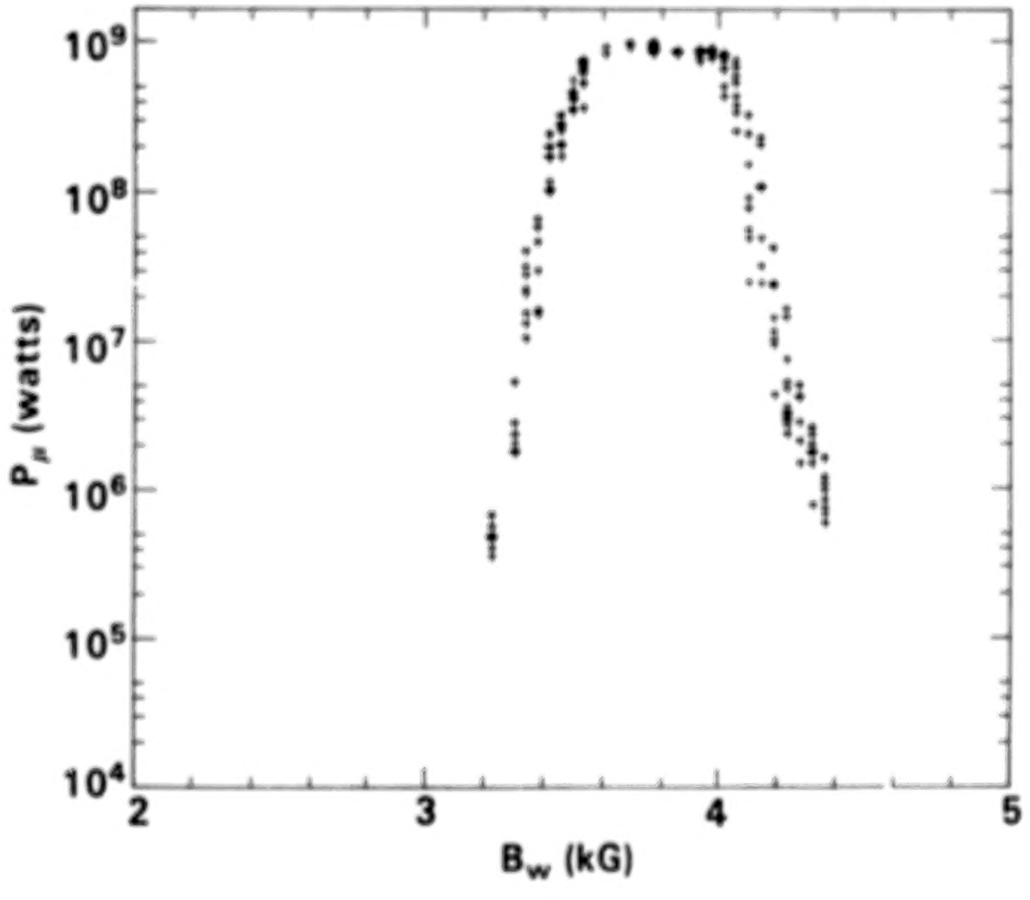
Results for output power versus wiggler length using the wiggler profile on the previous viewgraph. The solid line is the result of a numerical simulation.

Microwave power vs wiggler length:
tapered wiggler - B_w = 3.72 kG

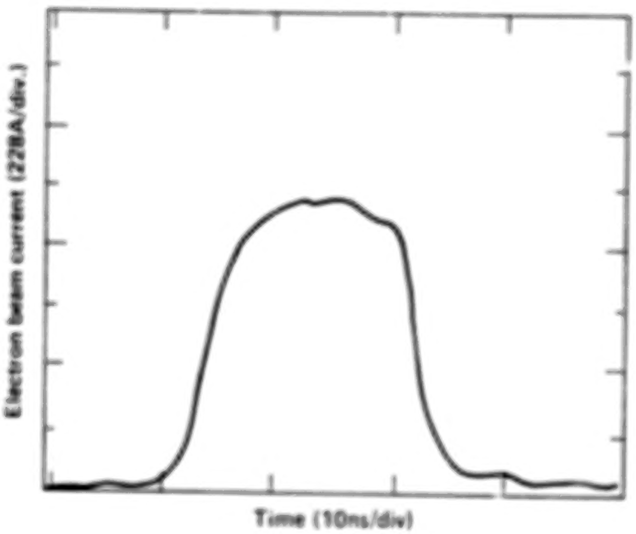


Power output as a function of wiggler magnetic field for a tapered wiggler. Compare this with the "detuning" curve shown previously for a one-meter wiggler. Note the increased bandwidth of the resonance.

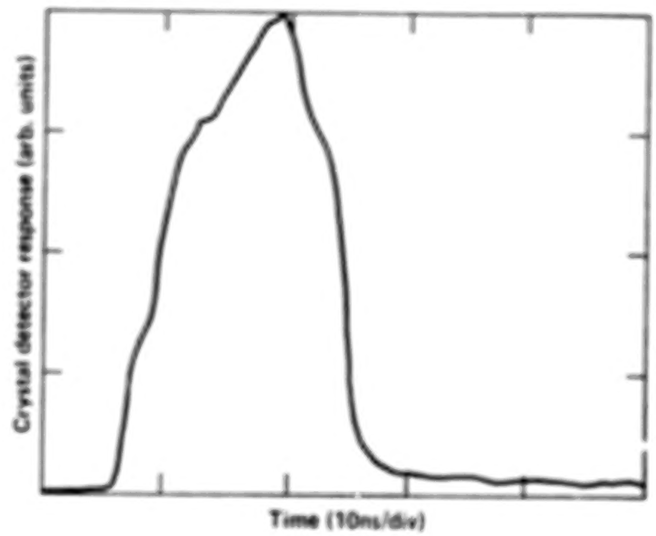
Detuning curve: 3-m tapered wiggler



Experimental data indicate efficiencies in excess of 40%

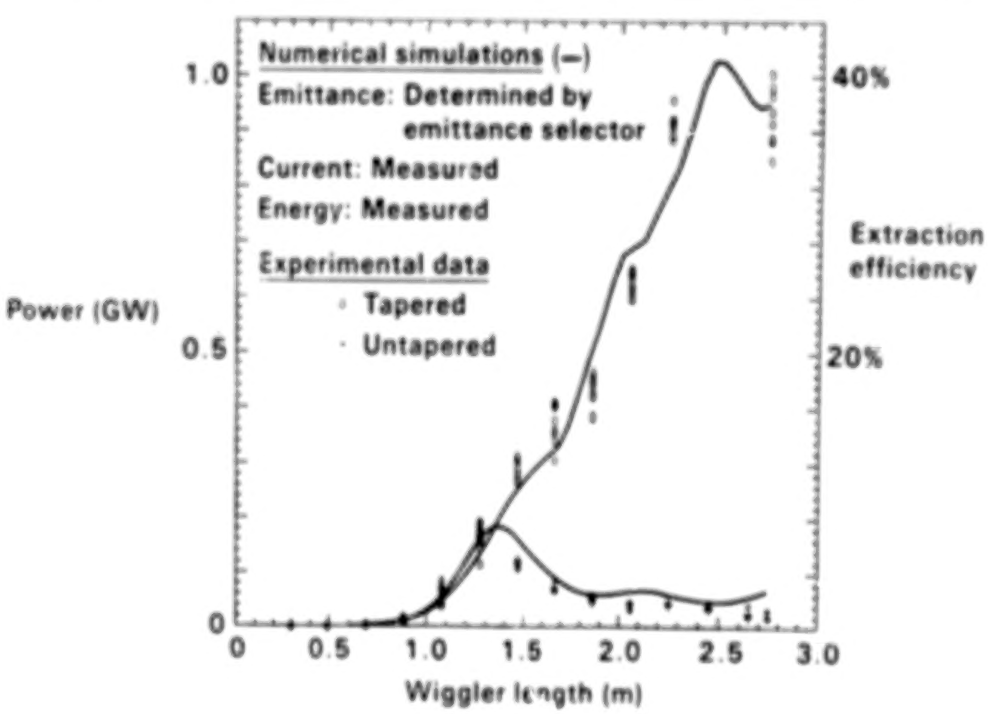


Electron beam energy = 3.5 MeV
Electron beam current = 1090 A
Electron beam power = 3.8 GW



Microwave power: 1.82 GW peak

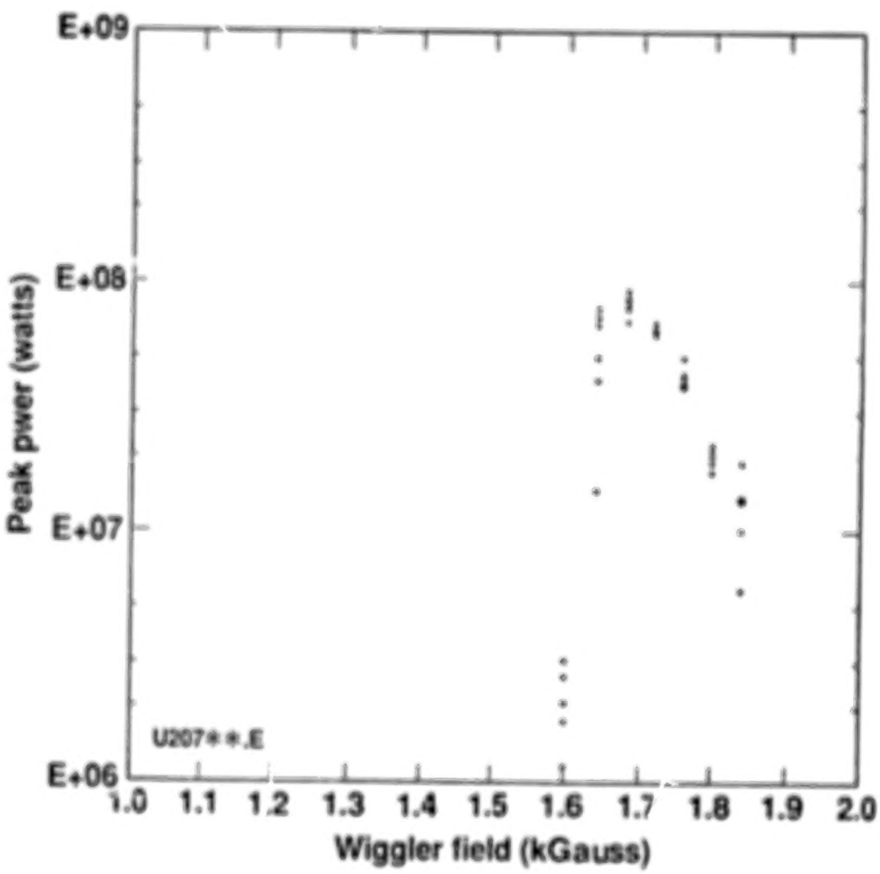
ELF clearly demonstrates the advantage of tapered wigglers



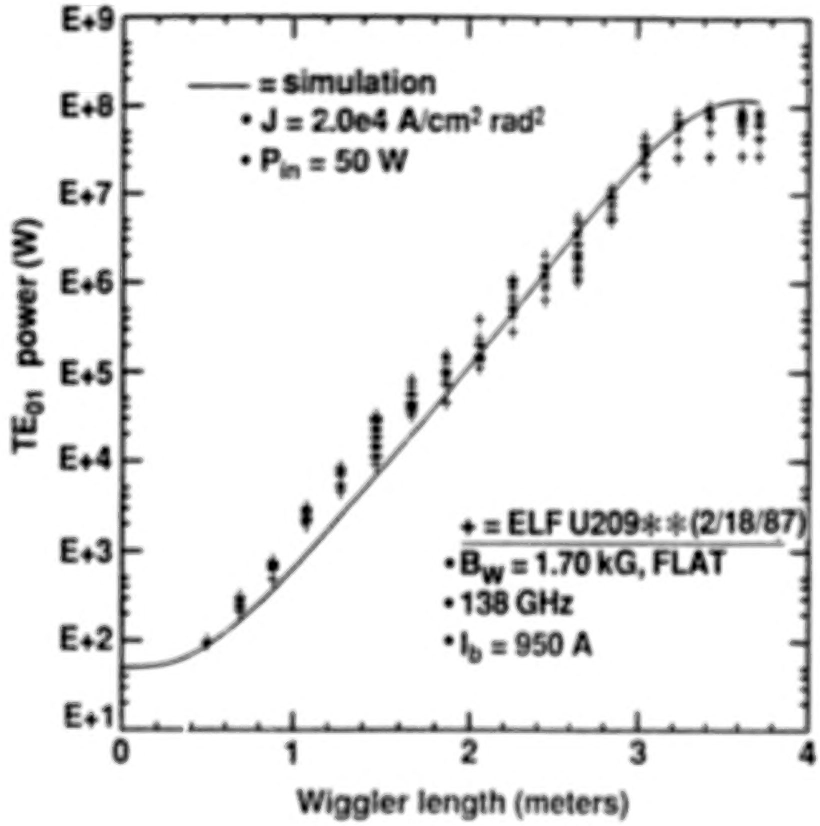
ELF operates as a 2mm amplifier

- 50 watt signal (f = 140 GHZ) injected into ELF interaction region
- Signal grows at 20 dB/m
- Signal saturates at P_S ~ 70 MW 3.2m into the interaction region

ELF detuning curve at 138 GHz — 4-meter flat wiggler



FRED simulations agree well with ELF results at 140 GHz



IMP is an integral part of a magnetic fusion experiment

- The ALCATOR tokamak is currently being reassembled at LLNL
- The microwave radiation from IMP will heat the tokamak plasma

Parameters for a 250 GHz FEL driven by an LIA operating at 5 kHz with 50 nanosecond pulse width.

IMP is designed to deliver high peak and high average power radiation

IMP design parameters:

E_{beam}	10 MeV
I_{beam}	3 kA
f_{μ}	250 GHz
P_{μ}(peak)	12 GW
% extraction	40%
P_{μ}(ave)	2 MW

IMP wiggler

L_w	5 m
λ_w	0.1 m
B_w (max)	4.5 kG

PALADIN is an optical FEL operating at 10.6 microns. The current operating parameters are listed on the following viewgraph.

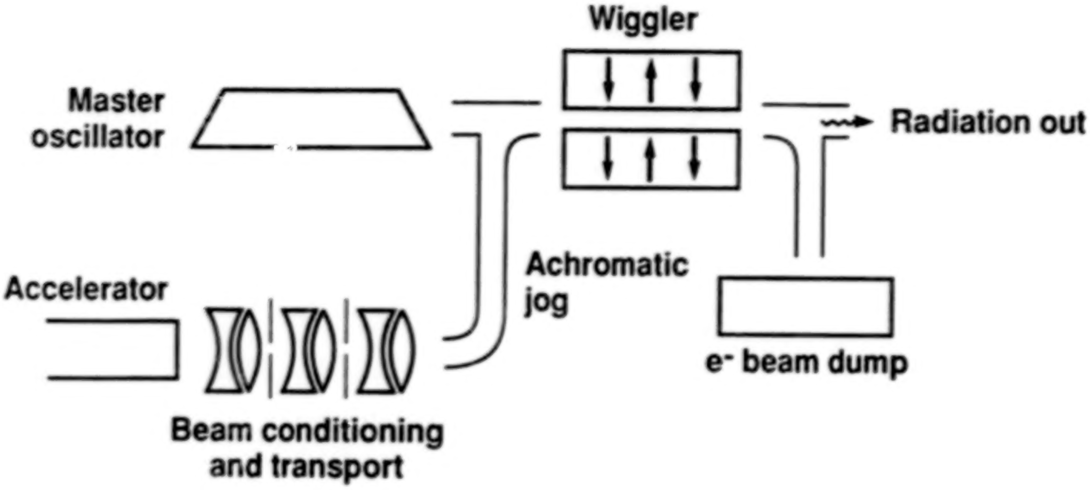
PALADIN Phase III experimental parameters

Wavelength	10.6 μ
Input signal	14 kW - 5 MW
Wiggler period	8 cm
Wiggler length	15 m
Raleigh range	5 m
Beam energy	45 MeV
Beam current	600-700 A
Beam brightness*	Mid-10^7 A/(rad-m)^2

*Assuming uniformly filled acceptance of quadrupole emittance selector

Schematic of the PALADIN beamline.

Principle components of a free electron laser amplifier



PALADIN Wiggler – General Specifications

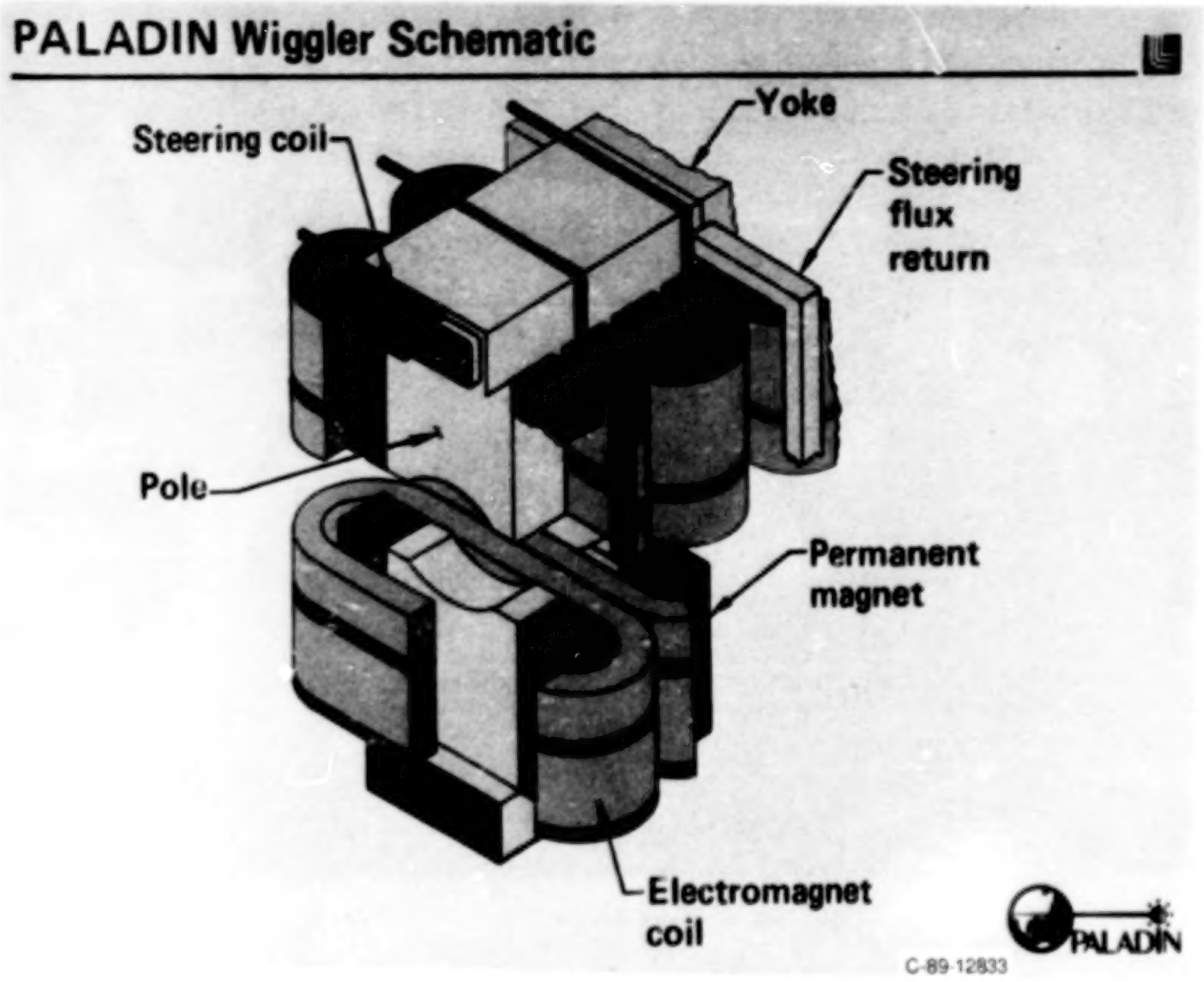
Laser wavelength	10.6 μm
Electron beam energy	50 MeV
Nominal wiggle field	2.5 kG
Period	8.0 cm
Pole-to-pole gap	3.0 cm
Overall length	5–25 m

Desired field profile:

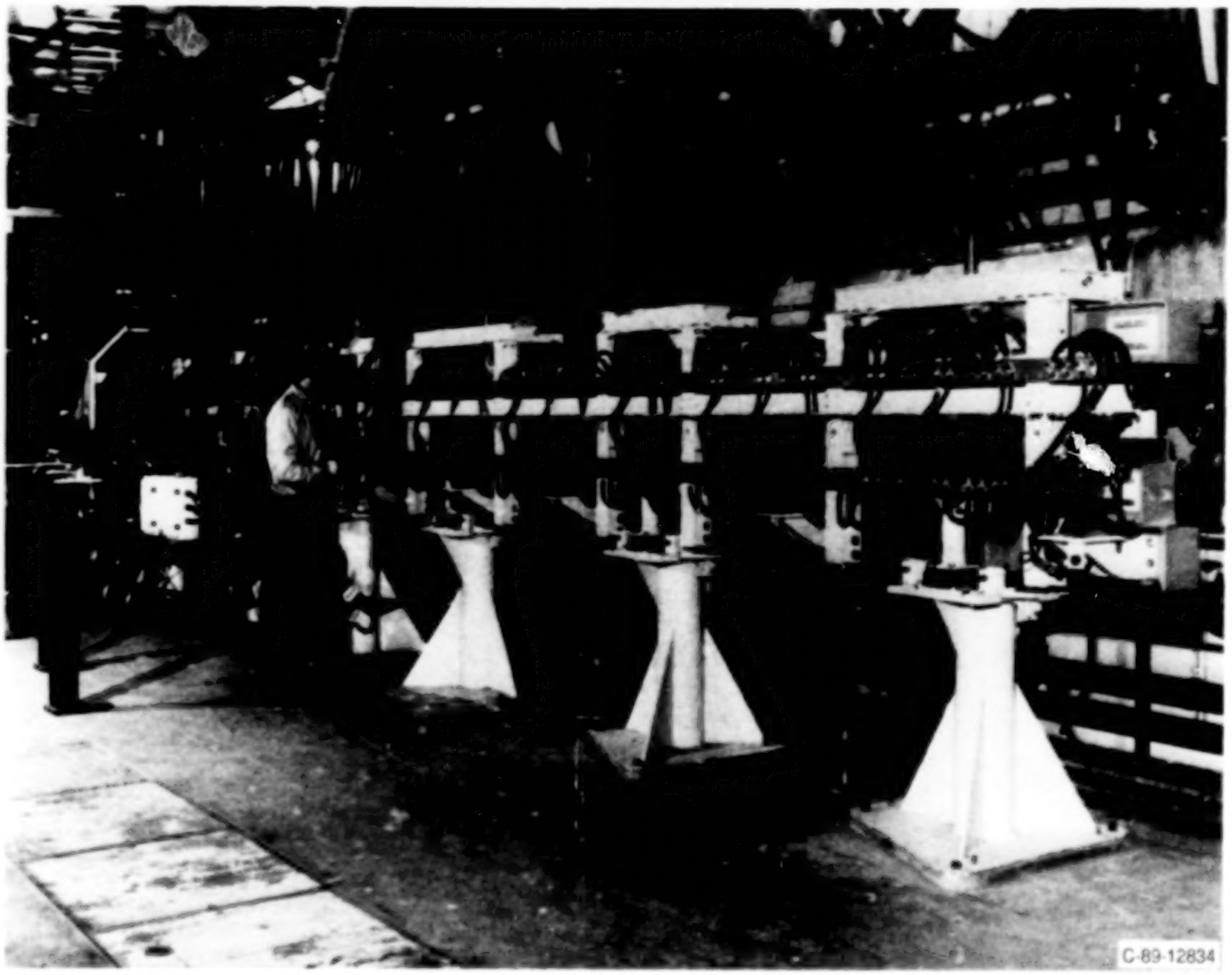
$$B_y = B_0 \cosh(k_0 x)\cosh(k_0 y)\cos(k_w z)$$

C.2

Schematic of one period of PALADIN wiggler. The iron core wiggler operates in a continuous mode. The specially shaped iron pole piece provides horizontal (wiggle plane) focusing.



Ten meters of the PALADIN wiggler during installation.



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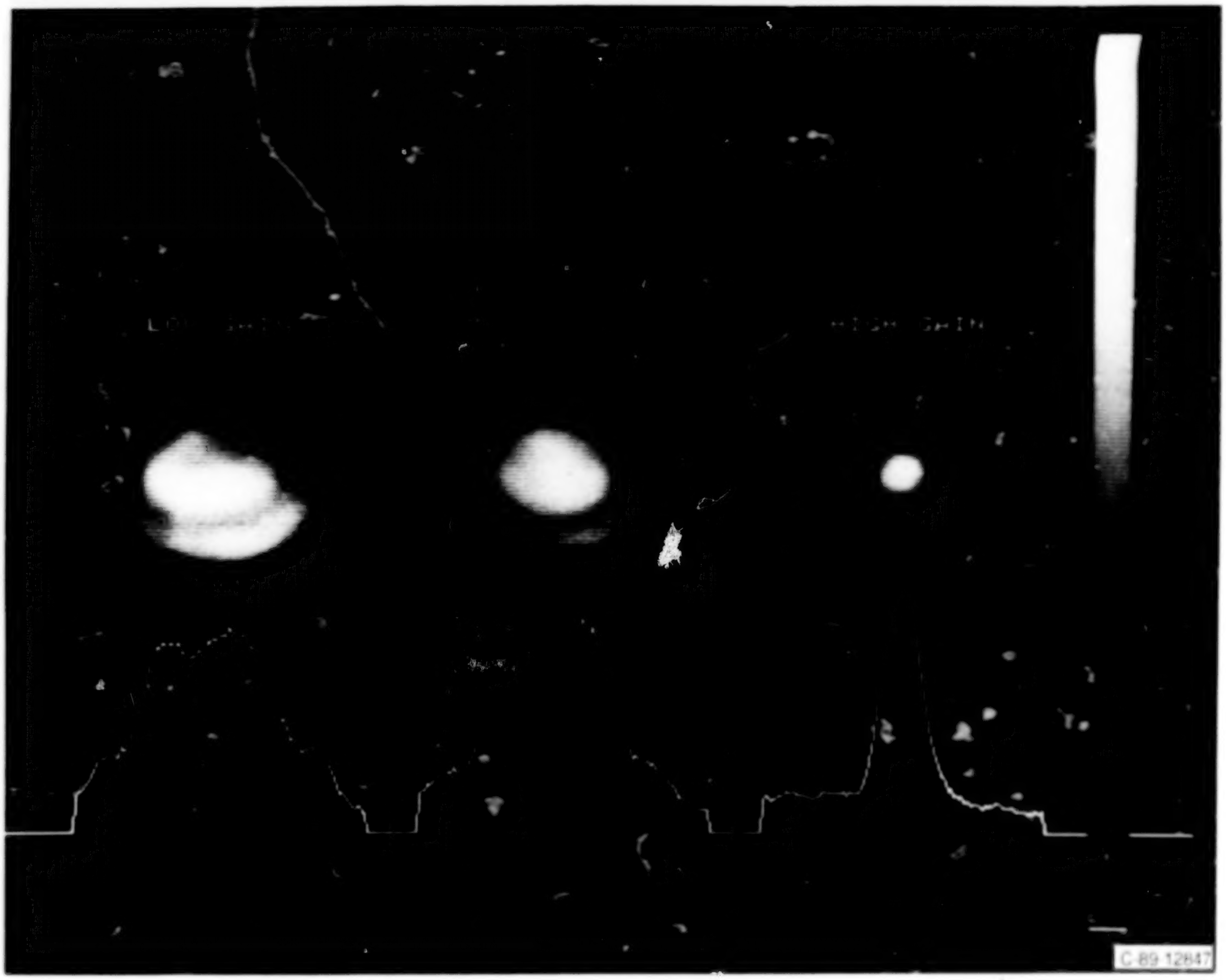
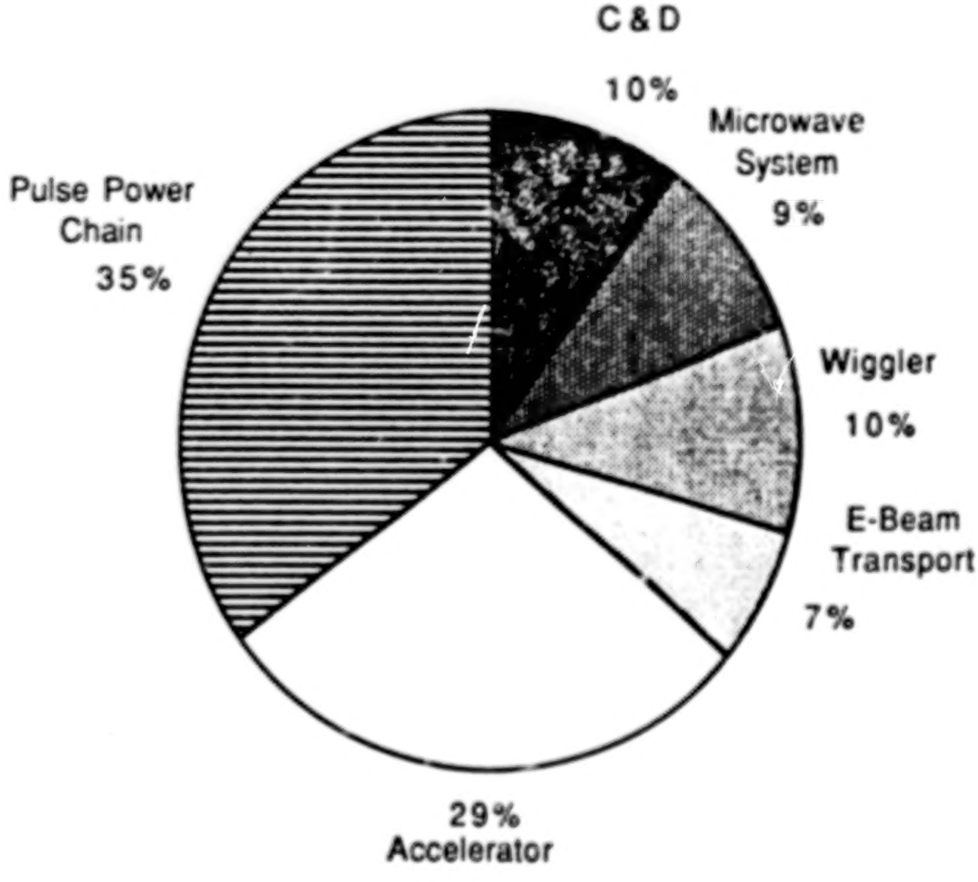
BLACK AND WHITE PHOTOGRAPH

Spatial profile at output of wiggler for three different gain conditions. (The medium and high gain cases are appropriately attenuated.) The high gain keeps the signal at a waist at the end of the wiggler. This is an excellent example of gain guiding.



The accelerator and pulsed power are the major cost items of a free-electon laser system.

Element cost breakdown indicates pulse power is major item



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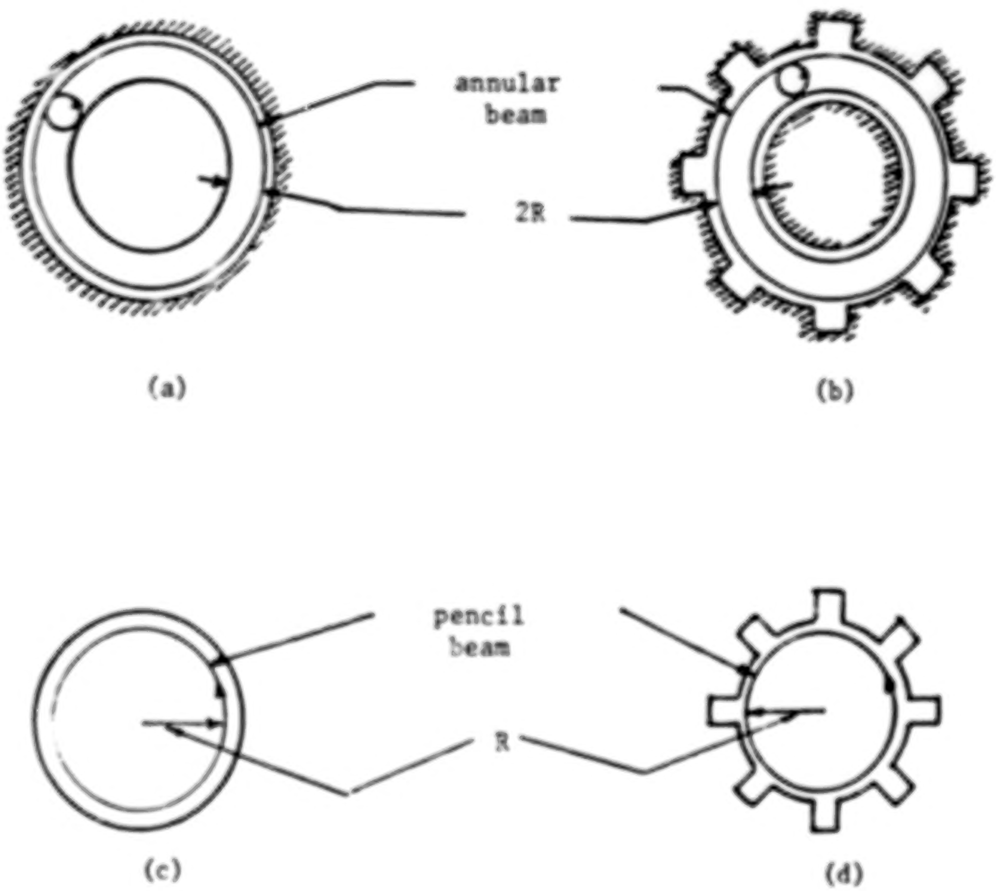
ANALYSIS OF A HIGH HARMONIC RECTANGULAR GYROTRON USING RIBBON BEAMS

Altan M. Ferendeci*
Case Western Reserve University
Cleveland, Ohio 44106



Cylindrical cavity structures and electron orbits in a) conventional, b) grooved coaxial, c) whispering gallery mode gyrotron and d) gyromagnetron. In b) the electrons see only a single ridge in their complete orbit. In a) and c) the electrons do not see any ridges at all during their complete orbit but generate highly efficient interactions with the electromagnetic fields.

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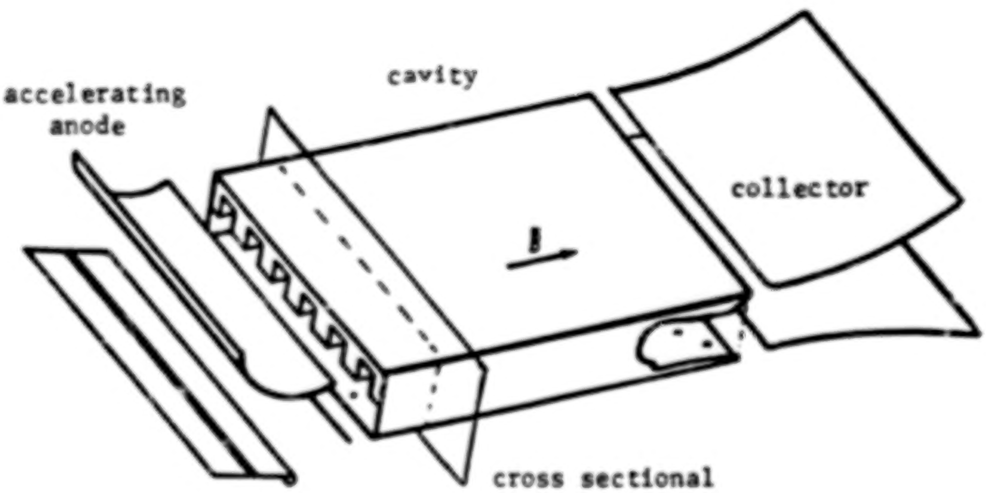
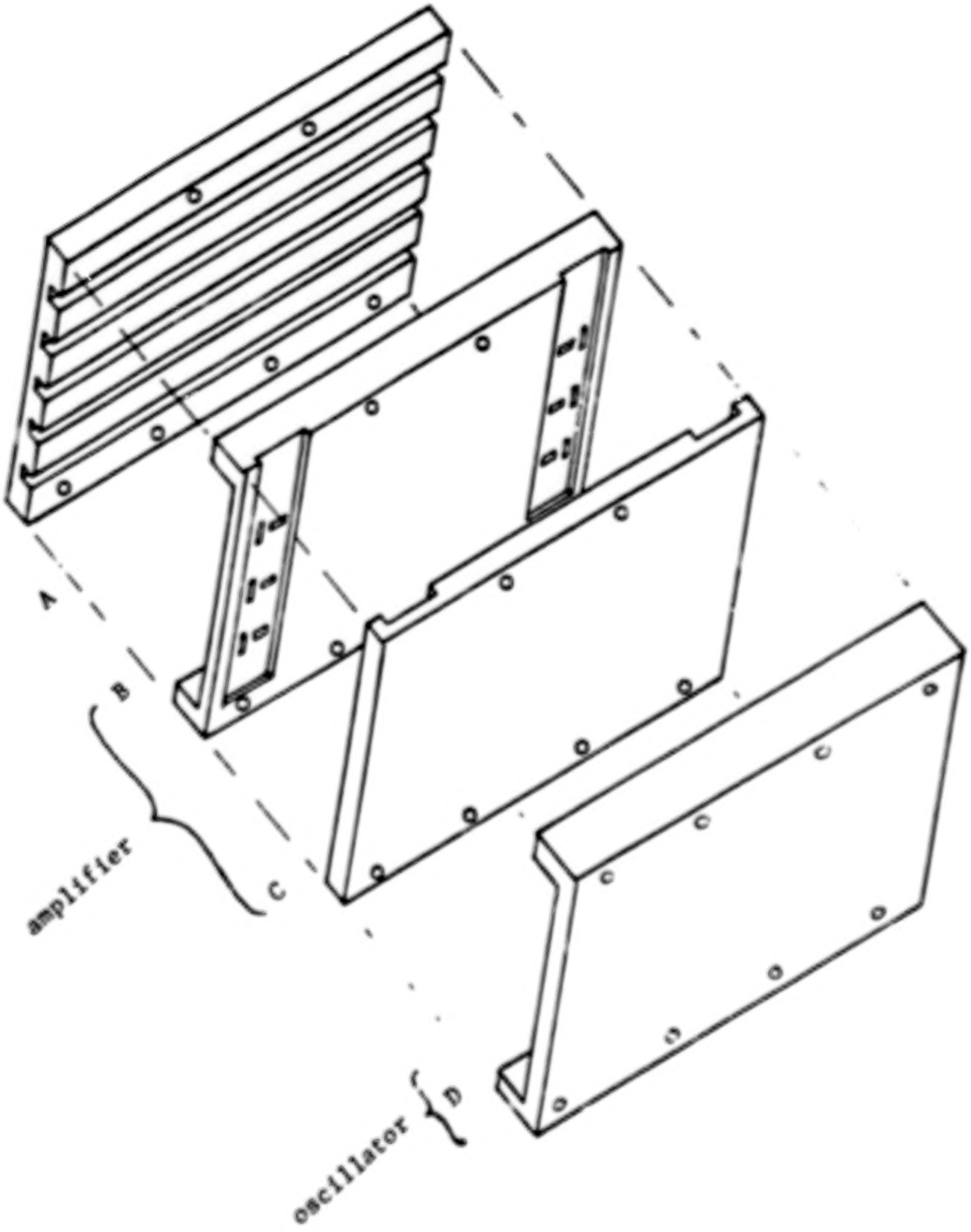
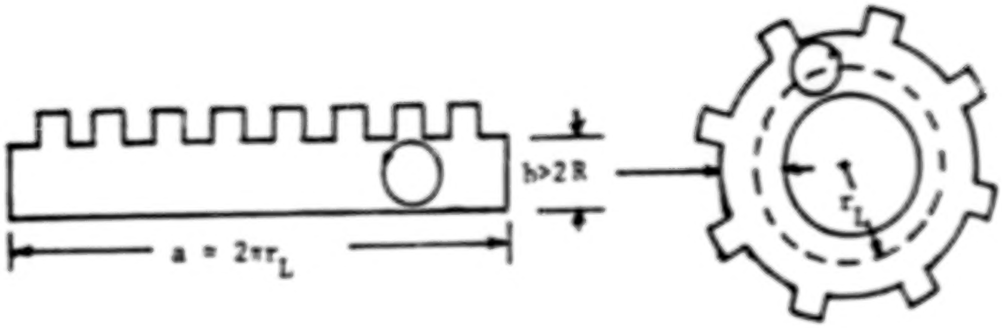
*Presently at Electrical & Computer Engineering Department, University of Cincinnati, Cincinnati, Ohio, 45221.



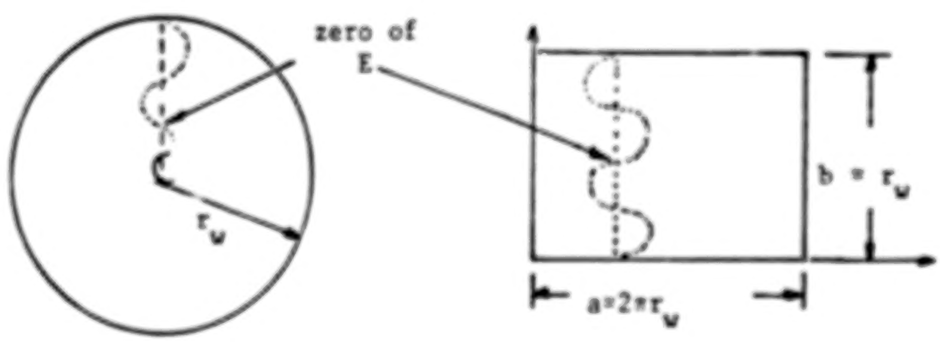
General schematic of an axially grooved gyrotron
using a ribbon beam.



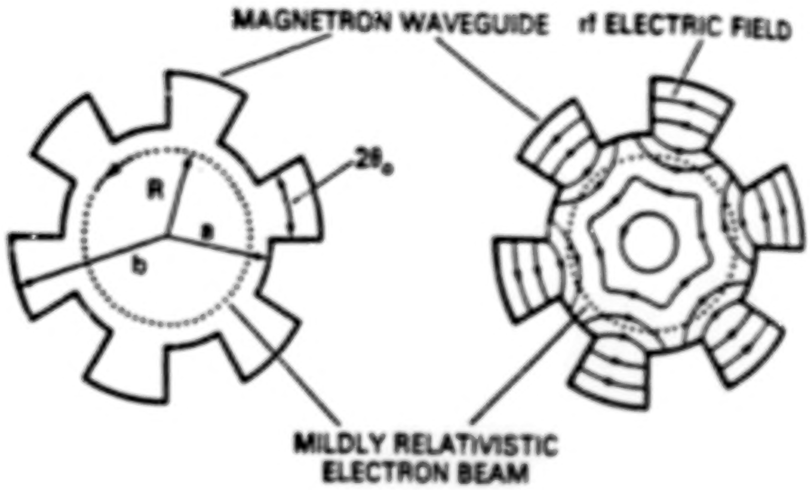
Constructional details. Upper grooved wall A is attached to the B and C for an amplifier or to D for an oscillator. B has coupling holes for input-output.



a - Folding a rectangular waveguide is equivalent to a coaxial waveguide.

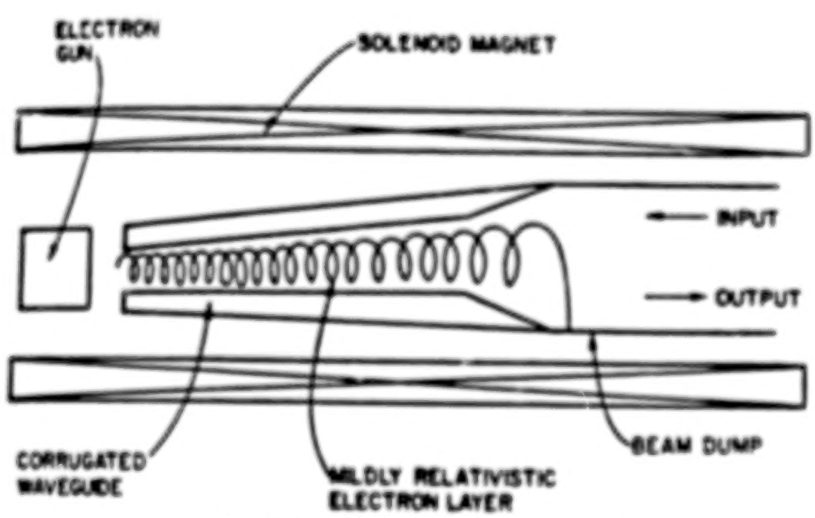


b - For fields to be compatible, only a rectangular waveguide with large dimensions but with small b/a ratio is equivalent to a circular waveguide having a few radial zeros.

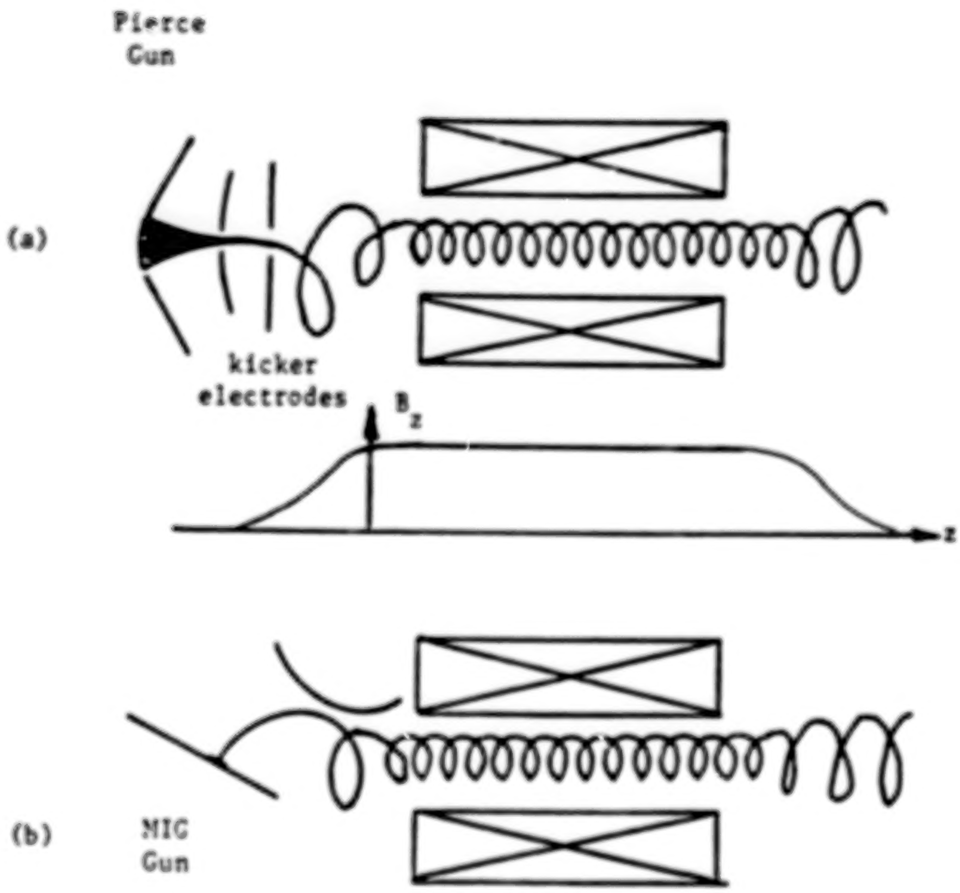


(a) Left. The cross-sectional view of a gyromagnetron with six vanes. (b) Right. Sketch of the rf electric fields of the 2π mode.

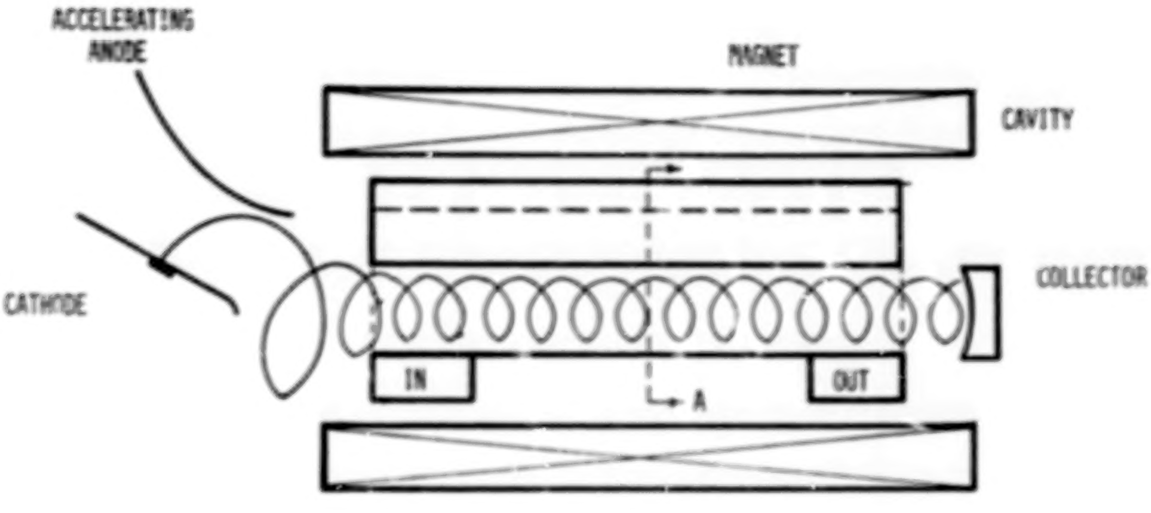
Low Magnetic Field Gyrotron



A schematic drawing of a low magnetic field, broad band, gyromagnetron amplifier



a) Ribbon beam using a conventional Pierce gun and kicker fields. b) Ribbon beam generated by a planar version of the MIG gun.

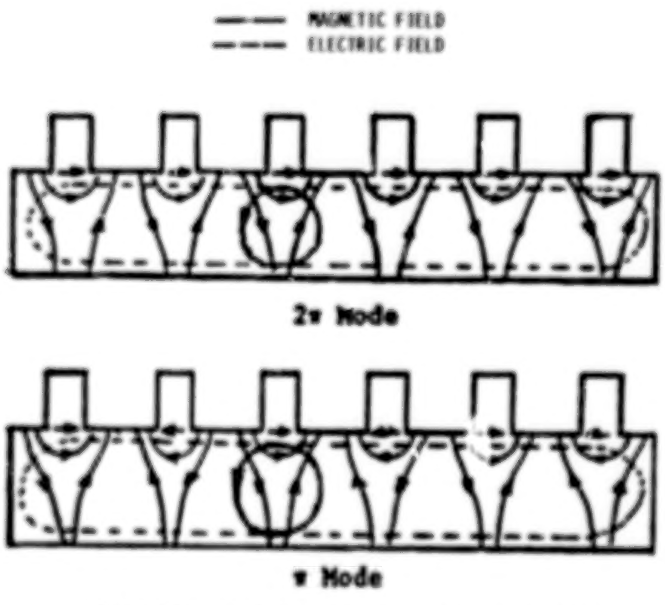


LONGITUDINAL CROSS SECTION OF GYROTRON AMPLIFIER

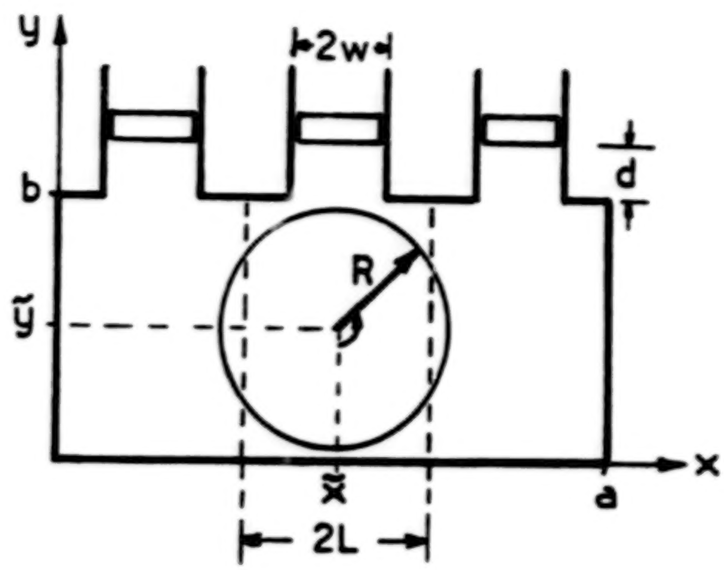
RESULTS

OPERATING FREQUENCY = 90 GH_z
HARMONIC NUMBER 5
$V_\perp$ = 0.4 C
V_z = 0.267C
$\nu = 2.2 \times 10^{-3}$ (9.5A)
P_b(BEAM CURRENT) = 670 KW

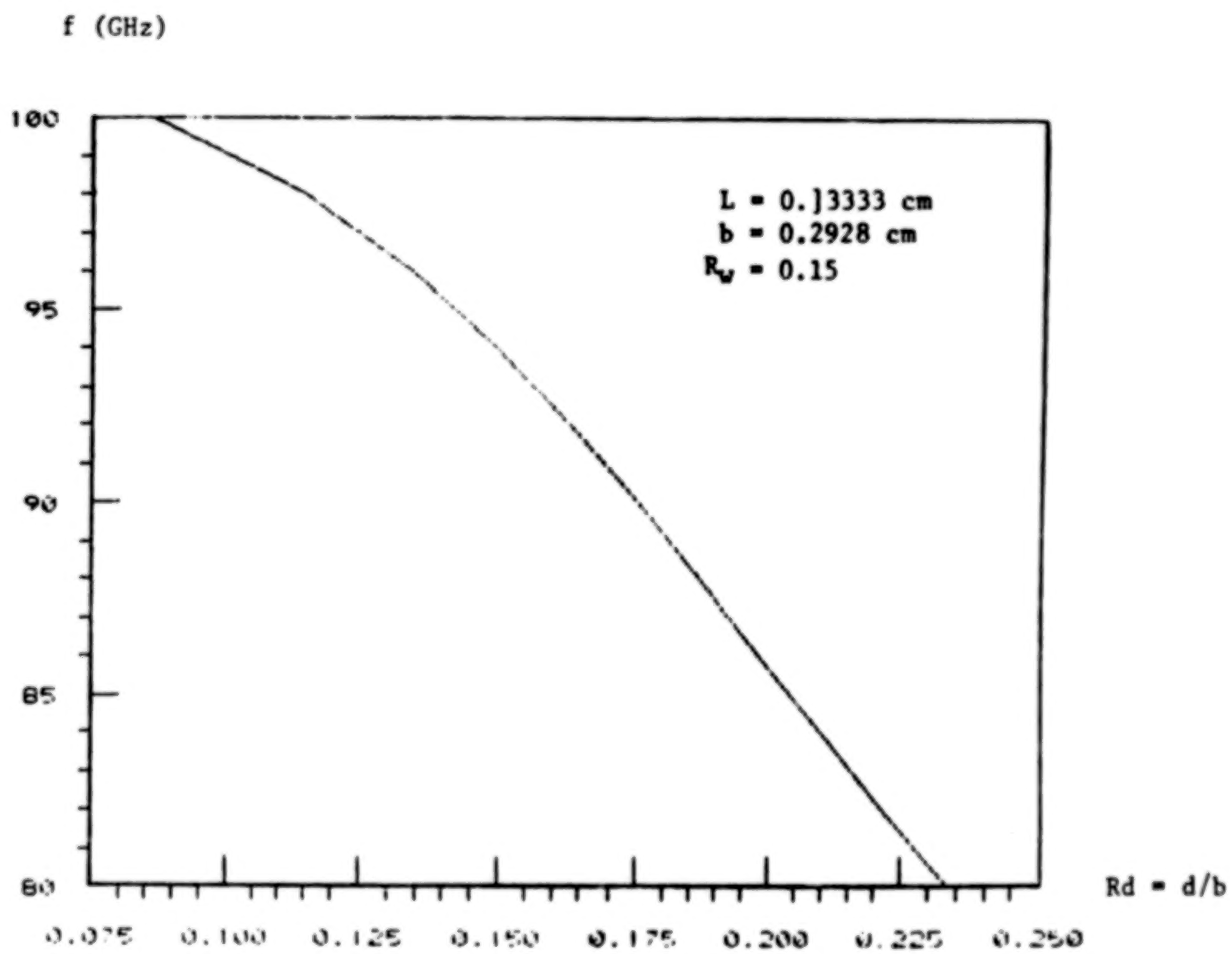
N = 3
a = 0.64 cm
b = 0.2928 cm
R_w = 0.15
R_d = 0.19



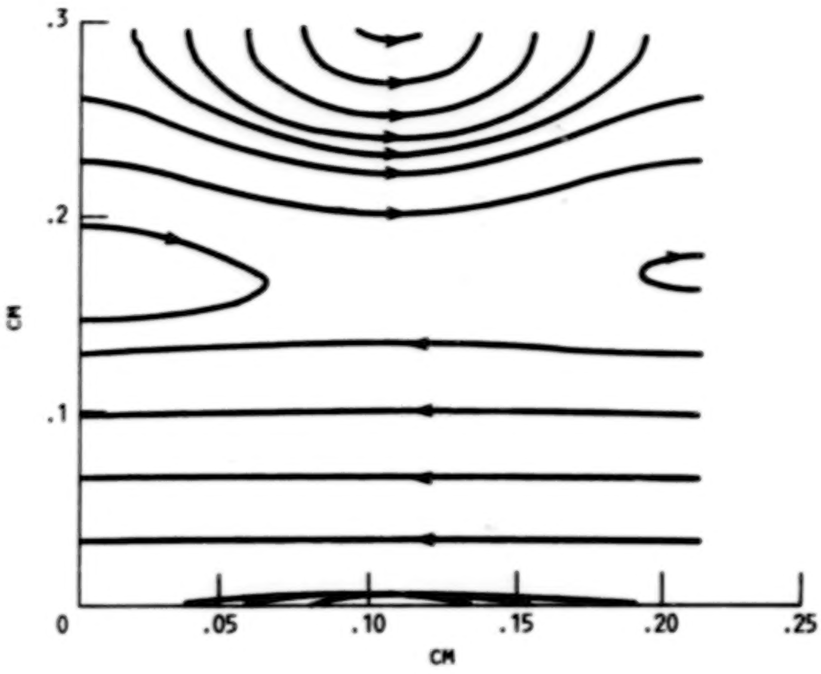
RADIATION PATTERN IN RECTANGULAR GYROTRON

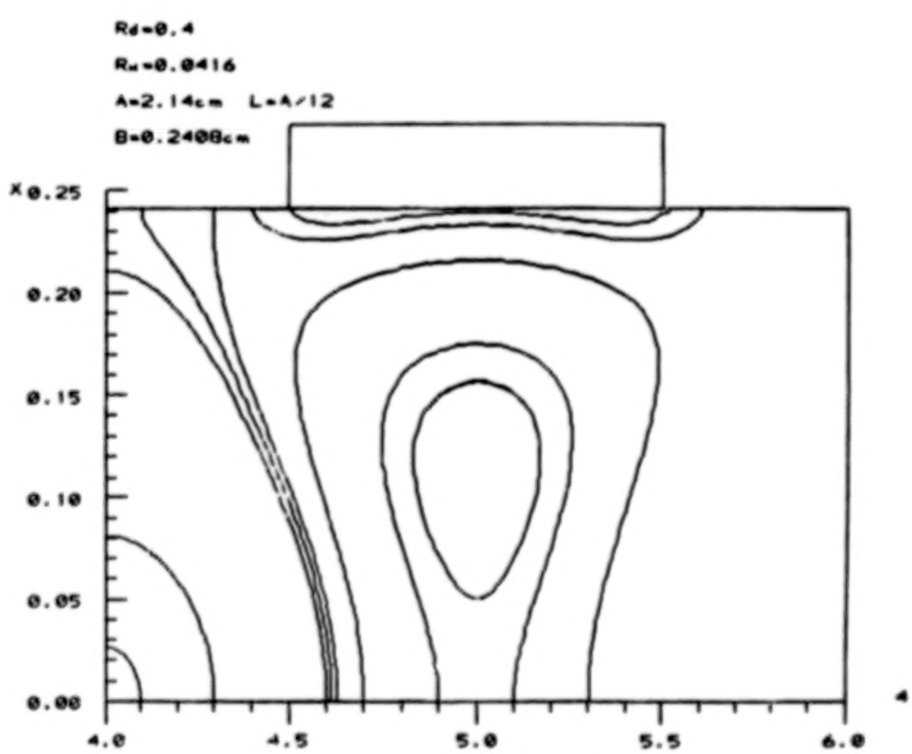


y
2w
b
d
R
ỹ
x̃
a
x
2L

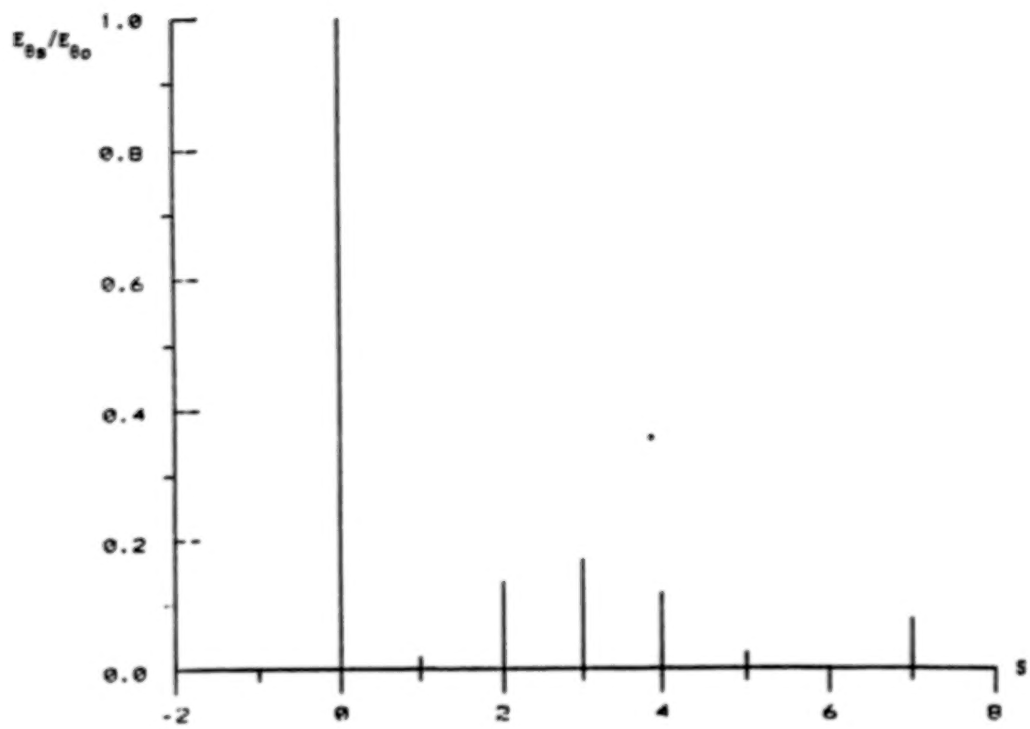


f (GHz)
100
95
90
85
80
L = 0.13333 cm
b = 0.2928 cm
R_w = 0.15
Rd = d/b
0.075
0.100
0.125
0.150
0.175
0.200
0.225
0.250

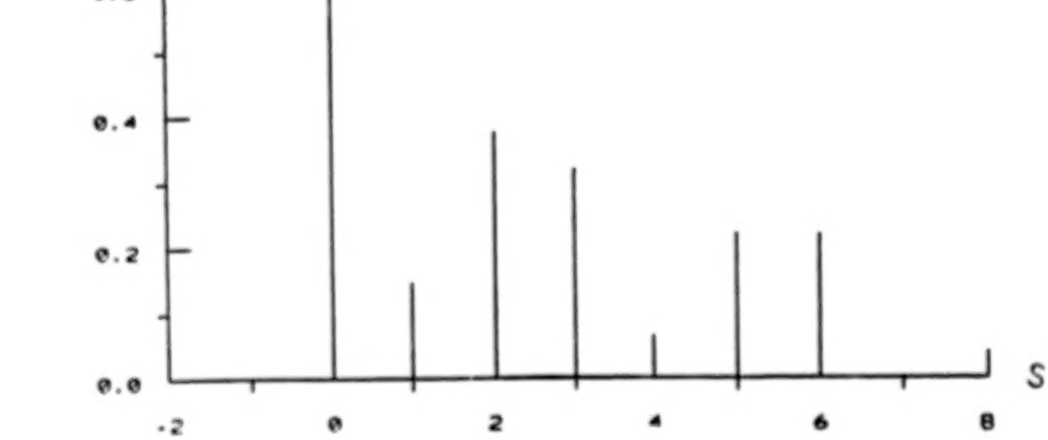




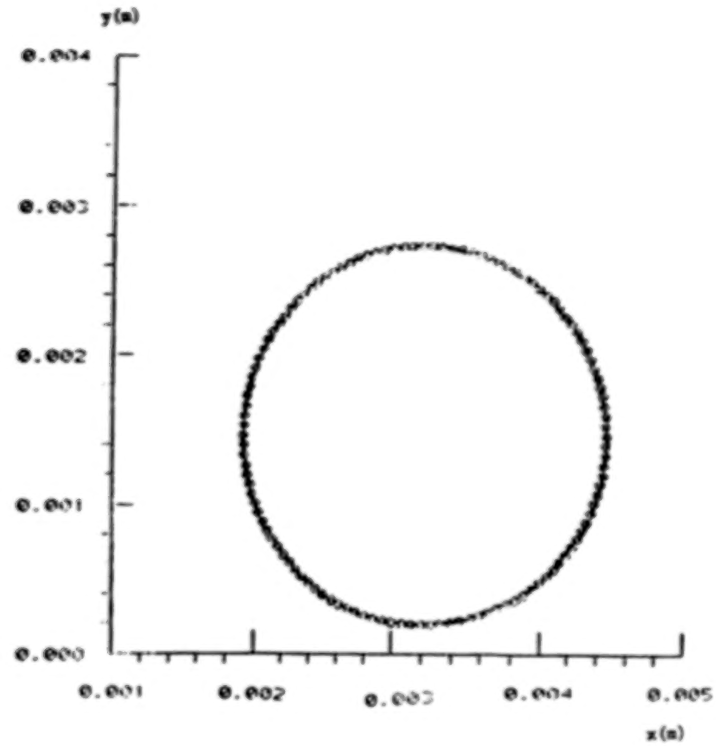
RADIATION DISTRIBUTION



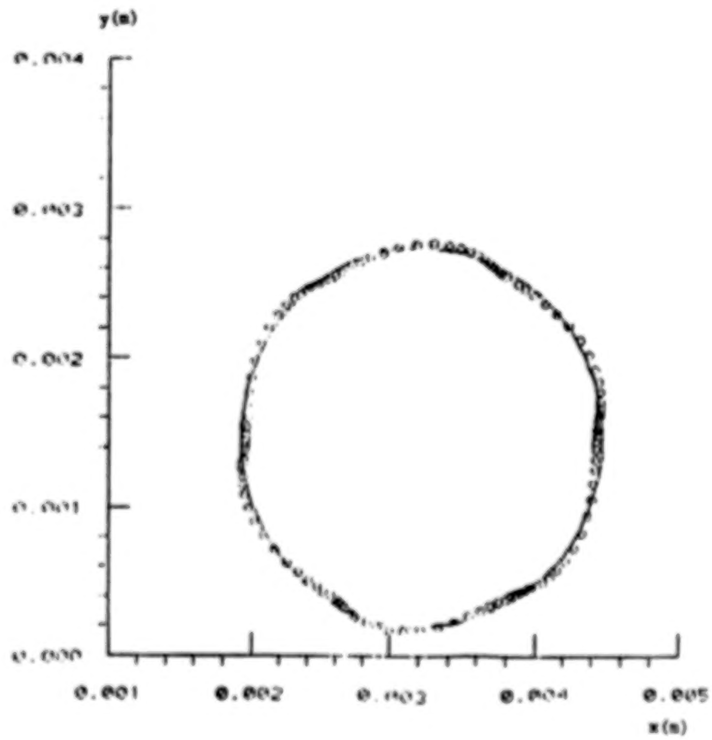
Fourier component spectrum of the tangential electric field



Fourier component spectrum of the tangential electric field



The initial phase distribution of an annular pencil beam which includes 120 electrons.



The phase distribution of the ensembled 120 electrons in linear region.

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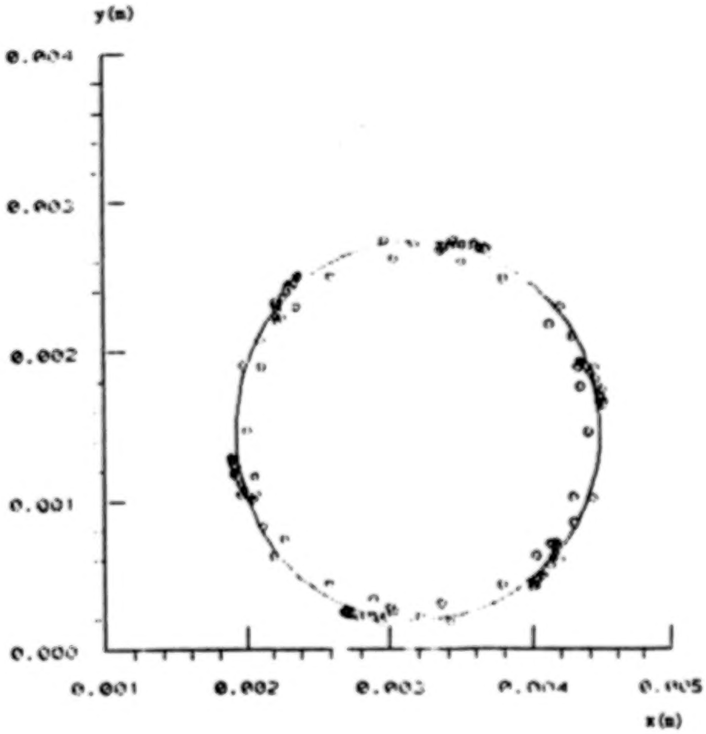

The phase distribution of the ensembled 120 electrons when the electrons regain energy from the field after saturation.

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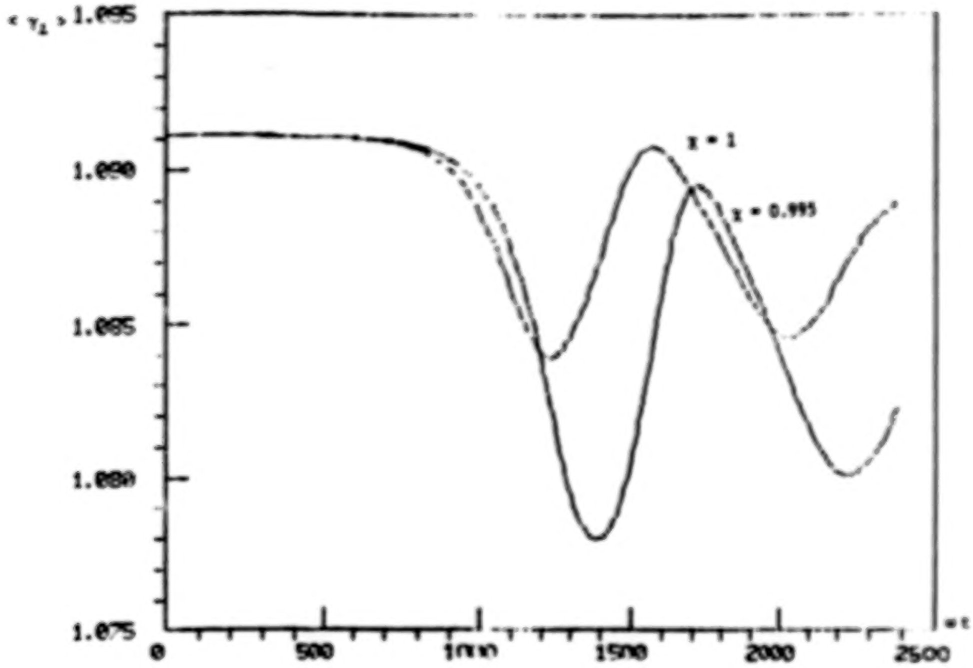
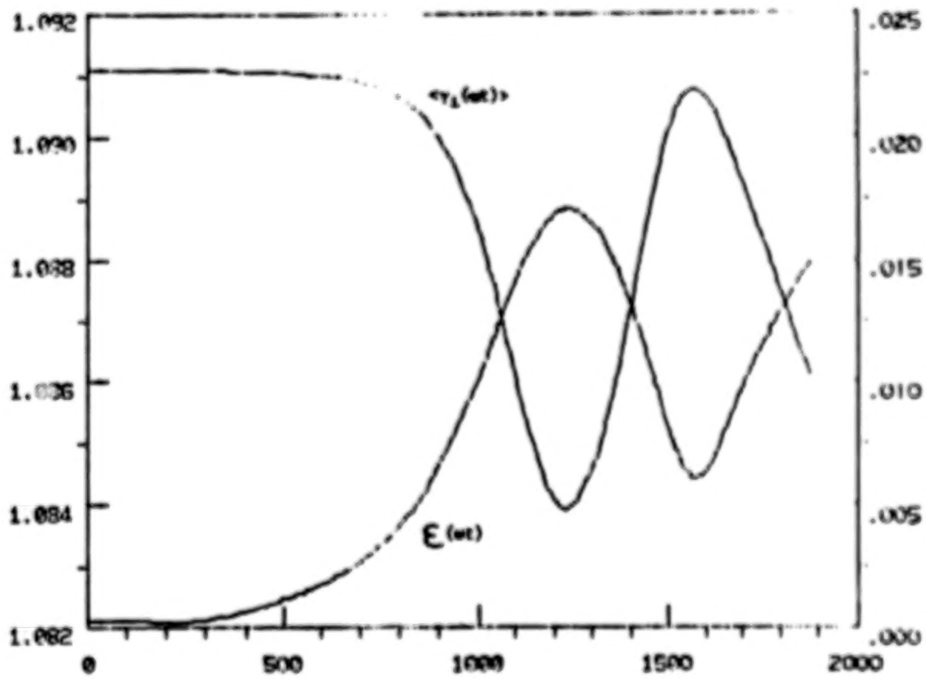
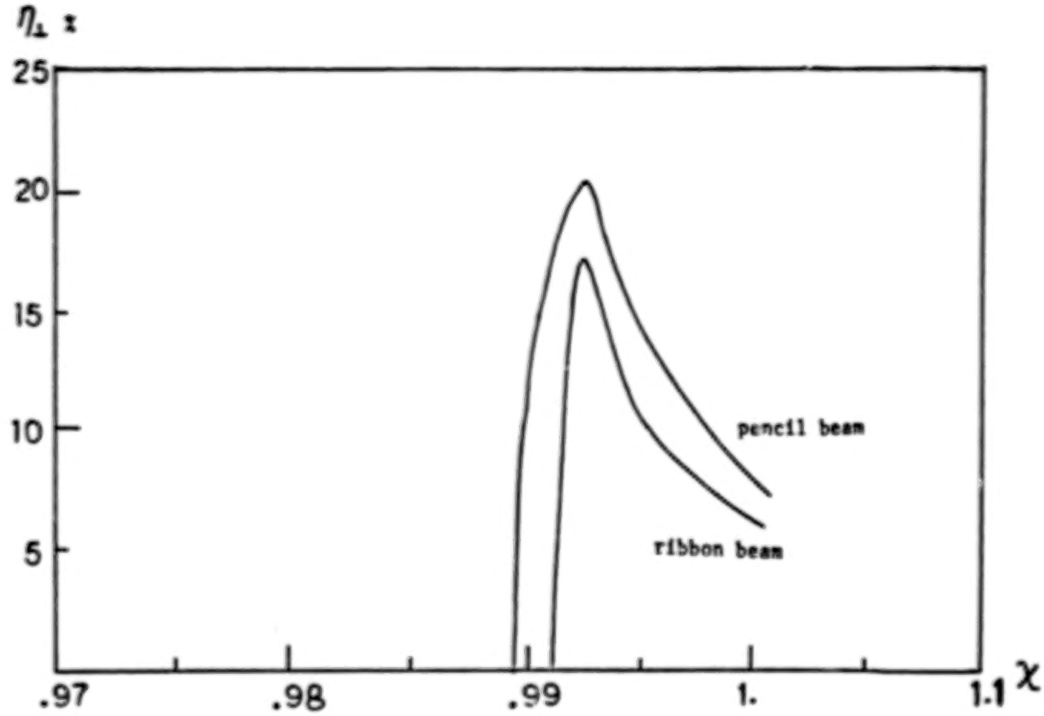


Energy curves with $\chi = 0.995$ and $\chi = 1$ respectively for a pencil beam at s=6.



The field amplitude and average beam γ as a function of ωt for a typical nonlinear simulation.



The energy conversion efficiencies of sixth cyclotron harmonic operation vs. χ for a pencil beam with its guiding center (a/2,b/2) and a ribbon beam at $\tilde{y}$=b/2.

ADVANTAGES

1 - ELIMINATION OF SUPERCONDUCTING MAGNETS

2 - REDUCED MODE COMPETITION PROBLEMS

3 - HIGHER POWER HANDLING CAPABILITY

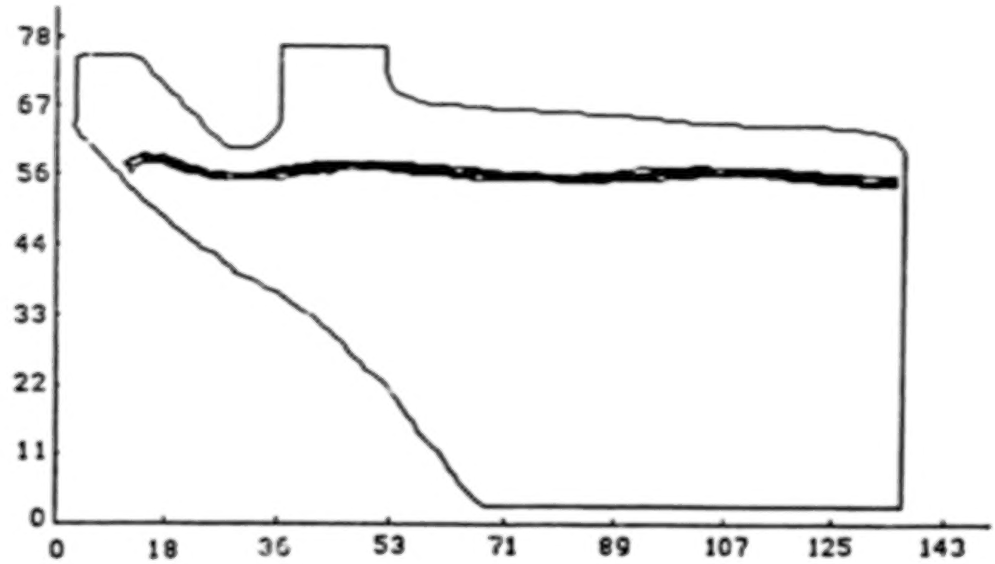
4 - REDUCTION OF SPACE CHARGE FORCES

5 - EASE OF MODIFICATION AS AN AMPLIFIER AND OSCILLATOR

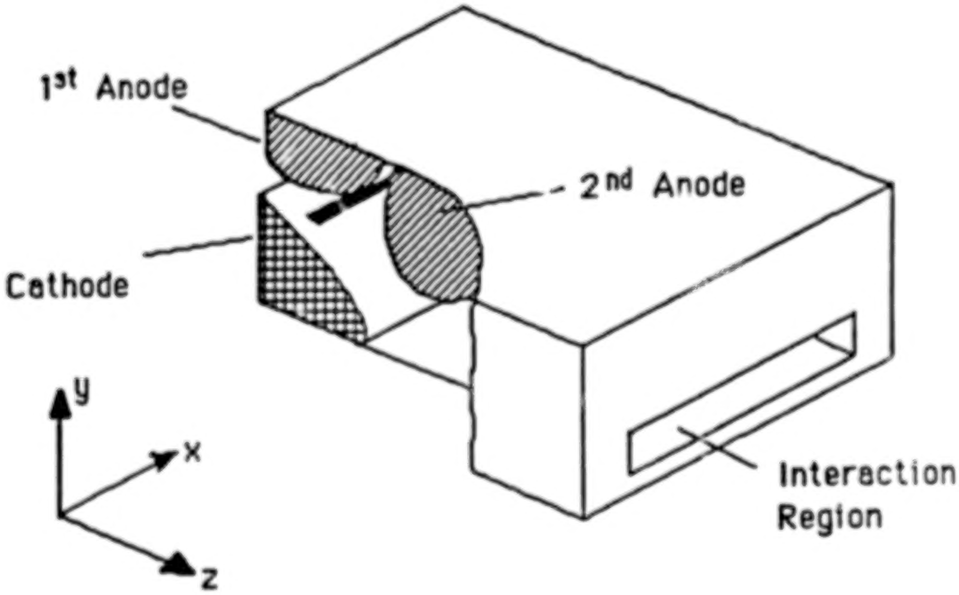
6 - EASE OF MACHINING

7 - SEPARATE INPUT-OUTPUT PORTS FOR AN AMPLIFIER

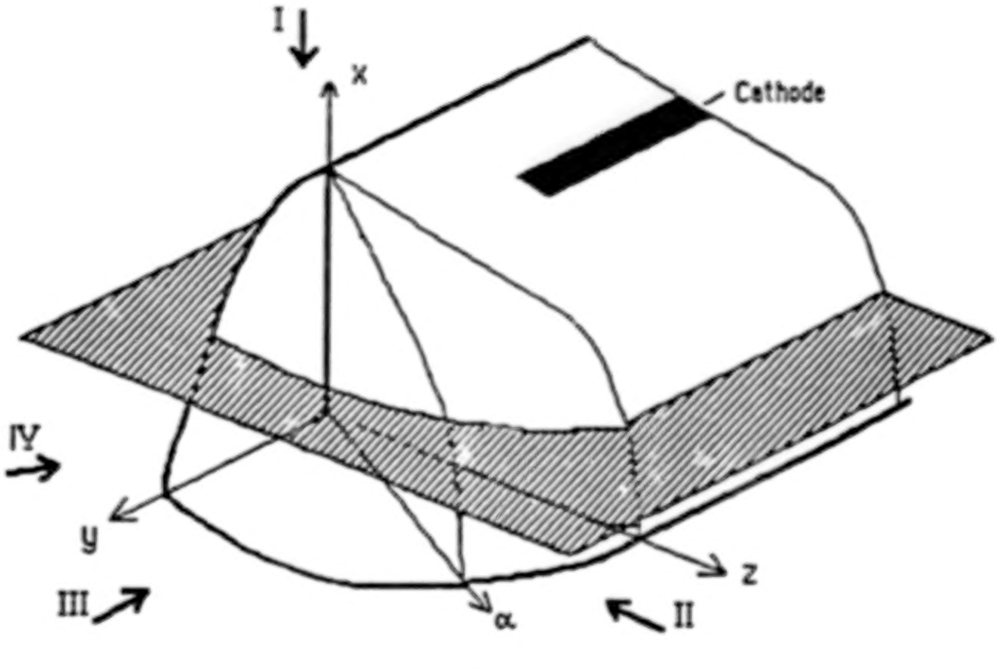
8 - BETTER EFFICIENCY AT HIGHER HARMONICS



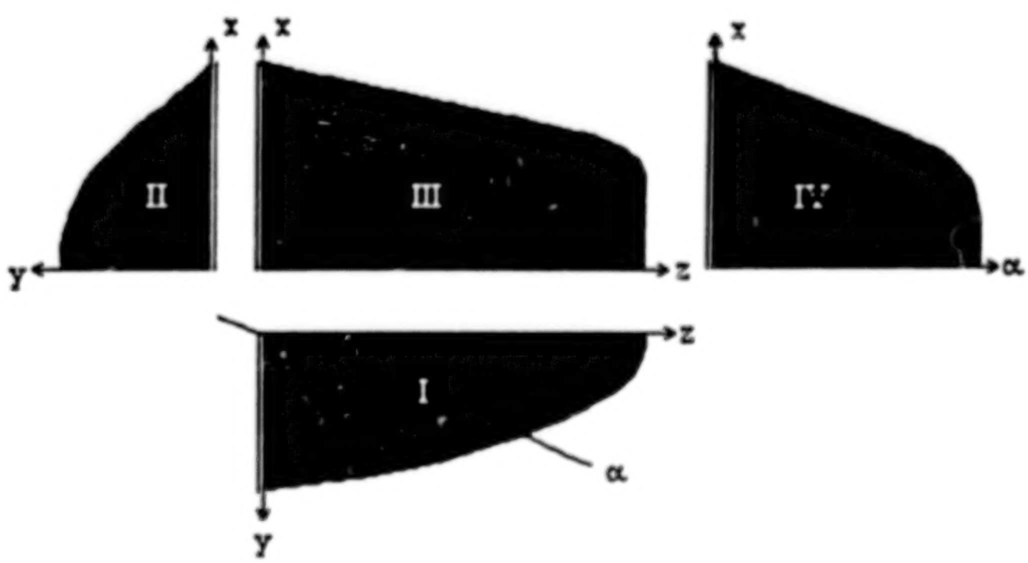
Simulation of the MIG gun whose boundaries are determined by computer bit mapping the boundaries of Fig.6. First anode potential $V_1 = 40$ kV and the final electrode potential $V_2 = 80$ KV. $B_o = 1$ KG in the axial direction.



Boundary identification is made by bit mapping the projections of the different electrodes onto different mutually perpendicular coordinate planes.

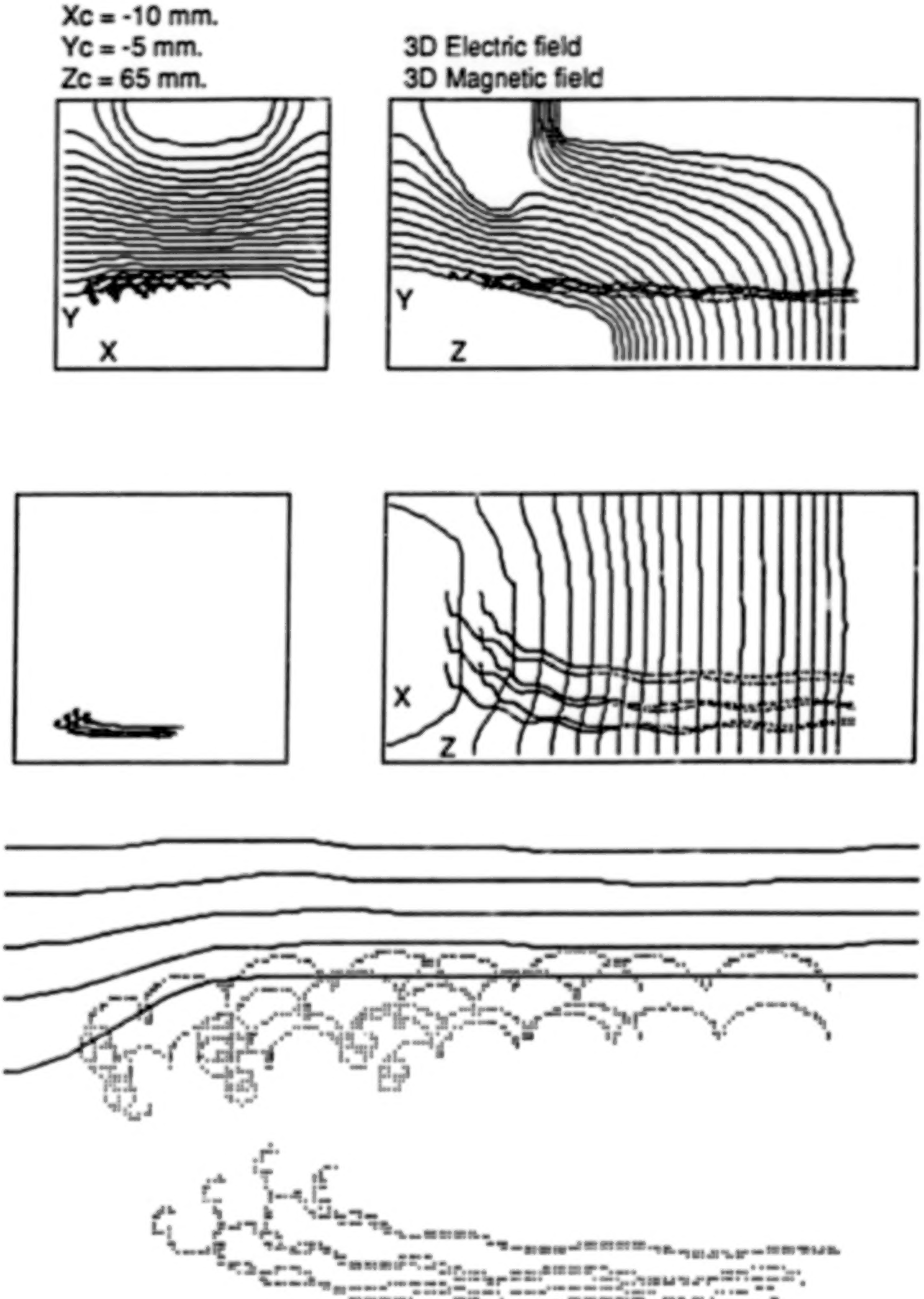


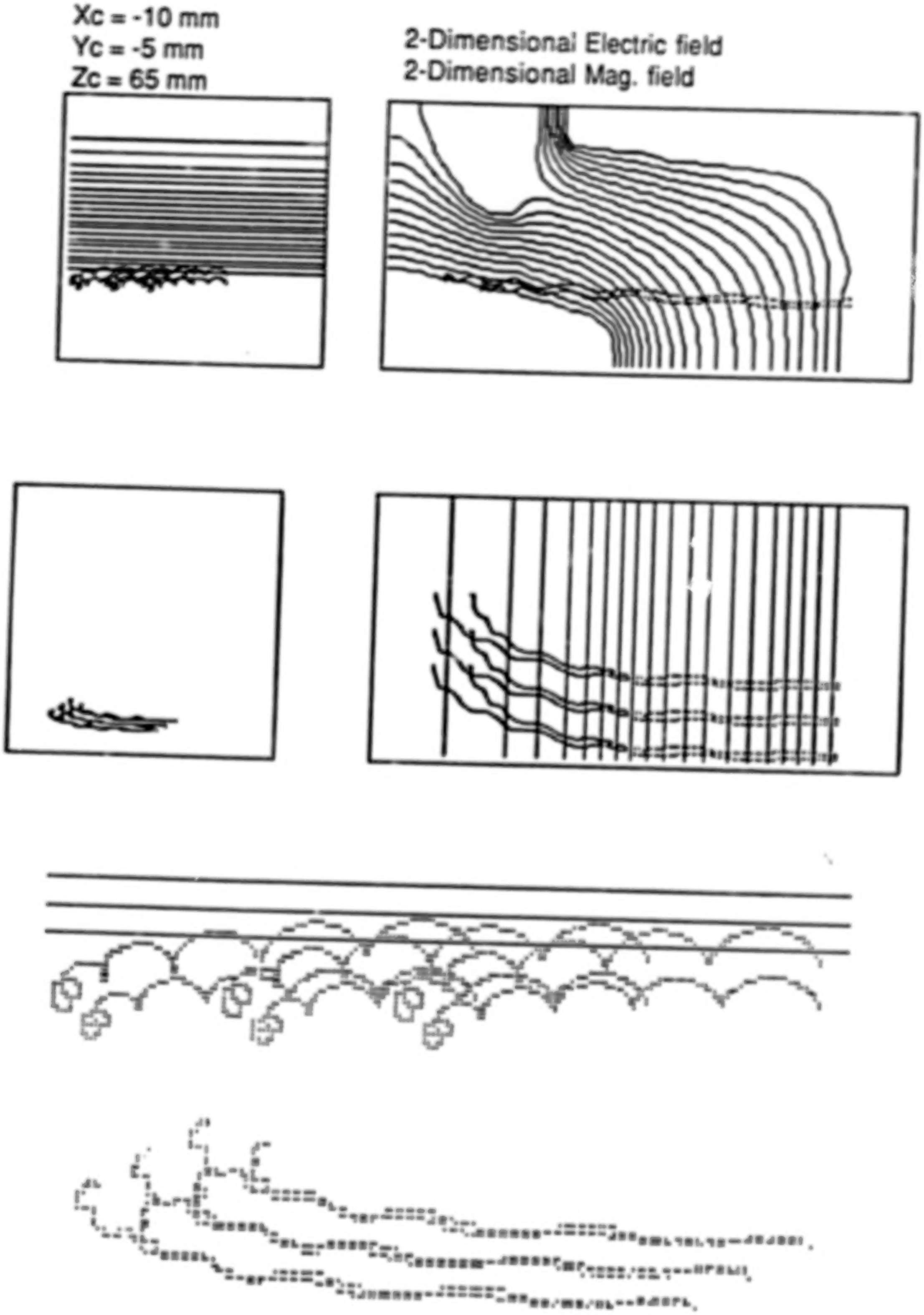
(a)



(b)

The projections of the cathode electrode at different planes. Projections I is in (y,z) plane, II is in(x,y) plane, and III is in(x,z) plane and IV is in an intermediate plane perpendicular to the (y,z) plane. Plane I is not necessary for many electrode profiles.


Xc = -10 mm.
Yc = -5 mm.
Zc = 65 mm.
3D Electric field
3D Magnetic field
Y
X
Y
Z
X
Z



Xc = -10 mm
Yc = -5 mm
Zc = 65 mm
2-Dimensional Electric field
2-Dimensional Mag. field

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OPERATION OF A STEP TUNABLE MEGAWATT GYROTRON*

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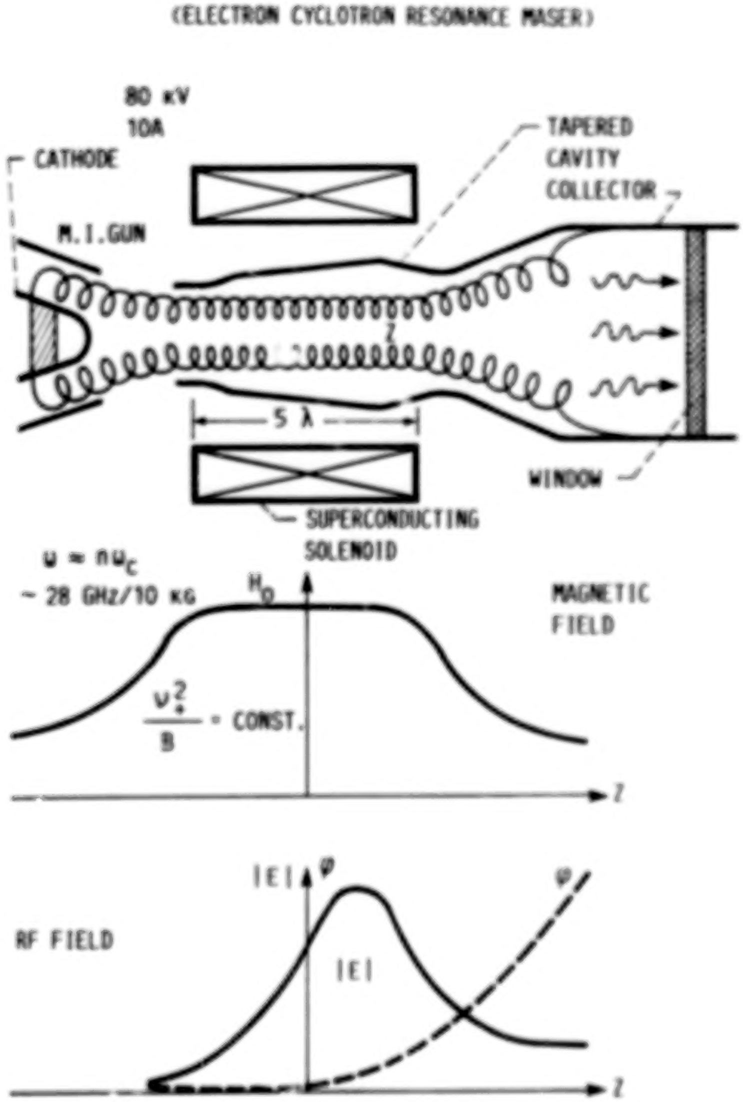
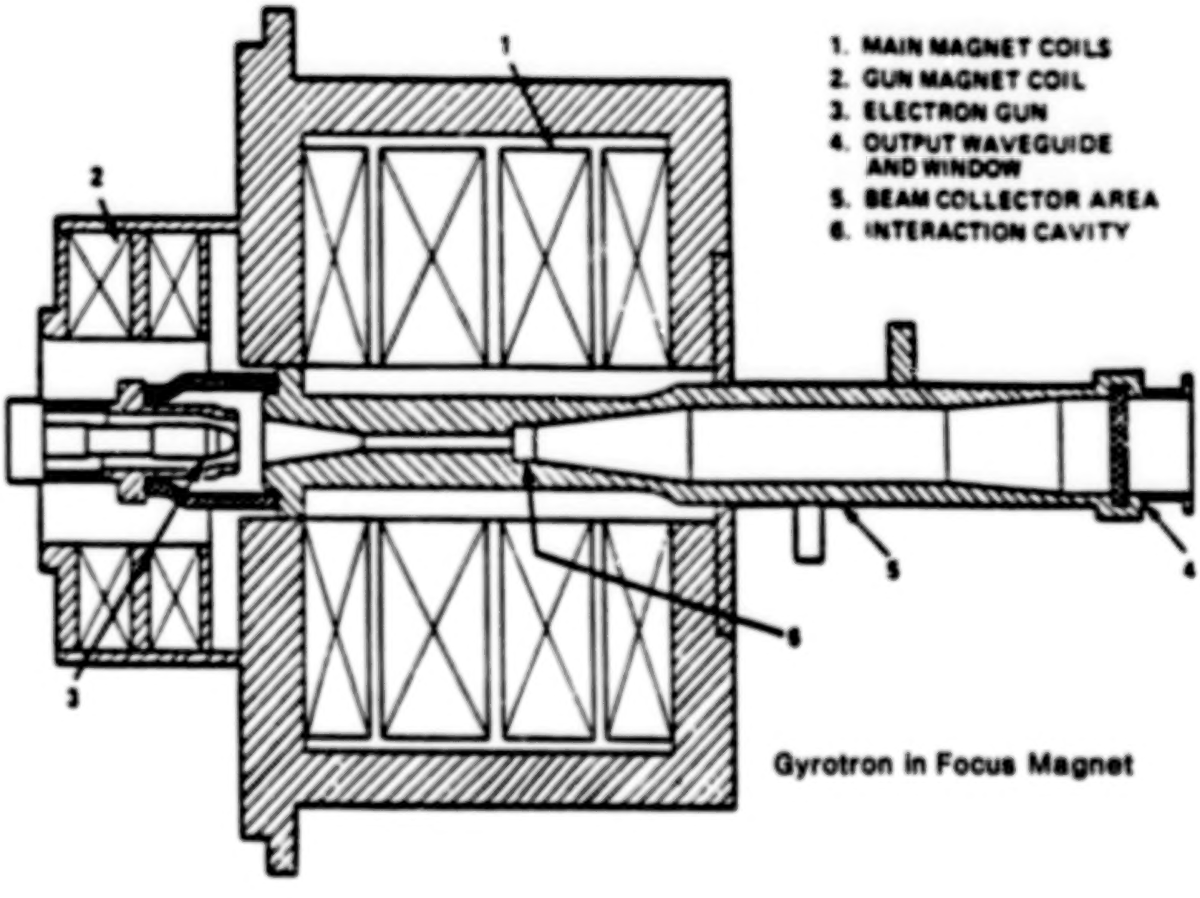
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139



*Work supported by the U.S. Department of Energy, Office of Fusion Energy.

GYROTRON FUNDAMENTAL OSCILLATOR

(28 GHz, 200 KW, CW, 80 KV, 8 A, length : 2m, B : 12 KG)



Gyrotron in Focus Magnet

Electrons are emitted from a small annular band on the electron gun or cathode, usually at a high negative voltage.

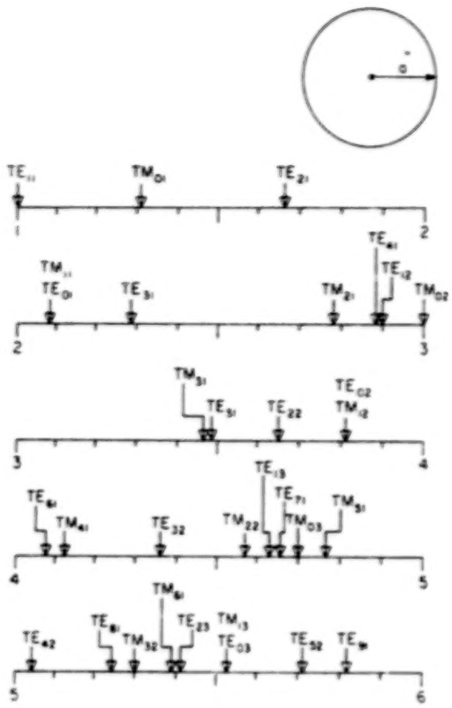


Fig. 5. Normalized modal cutoff frequencies for a circular waveguide.

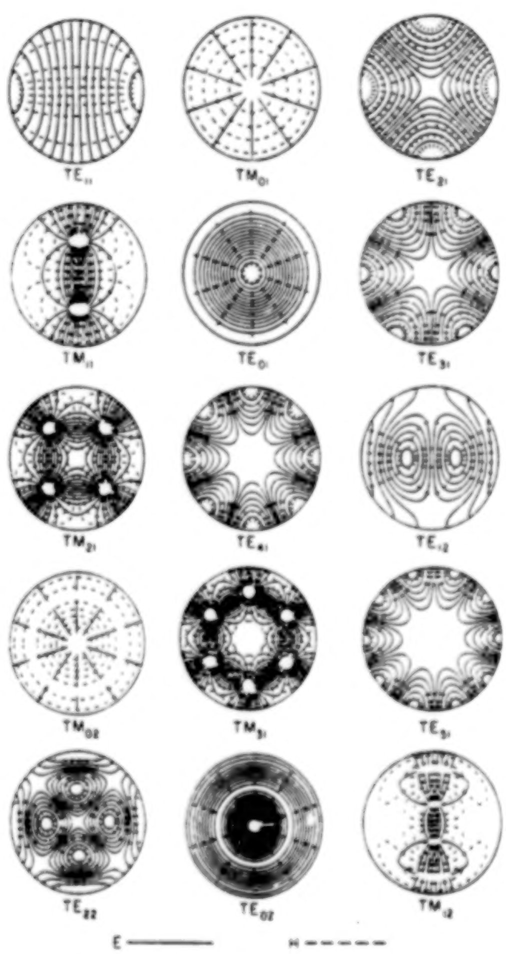


Fig. 6. Transverse modal field distribution for a circular waveguide (first 30 modes).

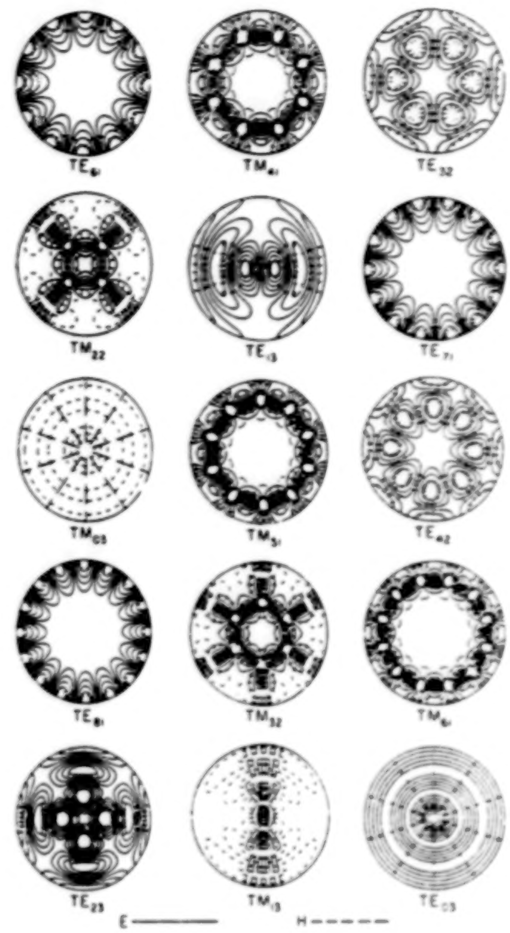
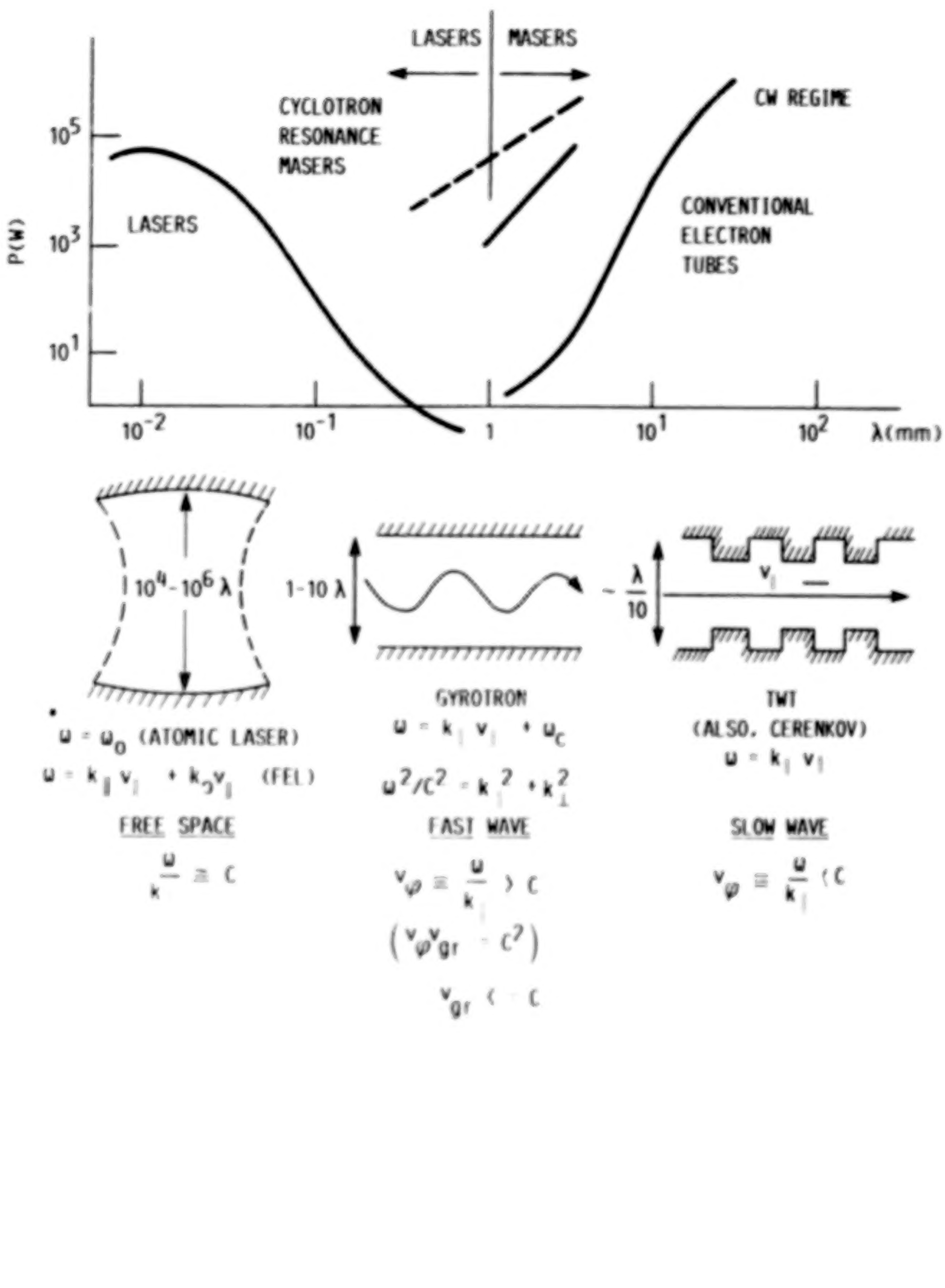


Fig. 6. (*Continued*)

Figures reprinted with permission from
Lee, C.S.; Lee, S.W.; and Chuang, S.L.: Plot of Modal Field Distribution in Rectangular and Circular Waveguides. IEEE Trans. Microwave Theory and Technol., vol. MTT-33, no. 3, Mar. 1985, p. 271.



LASERS
MASERS
CYCLOTRON RESONANCE MASERS
CW REGIME
CONVENTIONAL ELECTRON TUBES
P(W)
10^5
10^3
10^1
10^{-2}
10^{-1}
1
10^1
10^2
λ(mm)
10^4-10^6 λ
1-10 λ
~ λ/10
$v_\parallel$
GYROTRON
$\omega = k_\parallel v_\parallel + \omega_c$
$\omega^2/c^2 = k_\parallel^2 + k_\perp^2$
FAST WAVE
$v_\varphi \equiv \frac{\omega}{k_\parallel} > c$
$\left(v_\varphi v_{gr} = c^2\right)$
$v_{gr} < c$
TWT
(ALSO, CERENKOV)
$\omega = k_\parallel v_\parallel$
SLOW WAVE
$v_\varphi \equiv \frac{\omega}{k_\parallel} < c$
$\omega = \omega_0$ (ATOMIC LASER)
$\omega = k_\parallel v_\parallel + k_0 v_\parallel$ (FEL)
FREE SPACE
$\frac{\omega}{k} \cong c$

ADVANTAGES OF GYROTRONS

- MODERATE VOLTAGE OPERATION
  BELOW 100 kV. USE EXISTING SUPPLIES.

- INDUSTRIAL TECHNOLOGY BASE
  GOOD FABRICATION EXPERIENCE. RELIABILITY.

- CW OPERATION
  STABLE. BEST CHANCE TO USE A WINDOW.

- MODEST DEVICE SIZE
  LIKELY TO BE LEAST EXPENSIVE APPROACH.

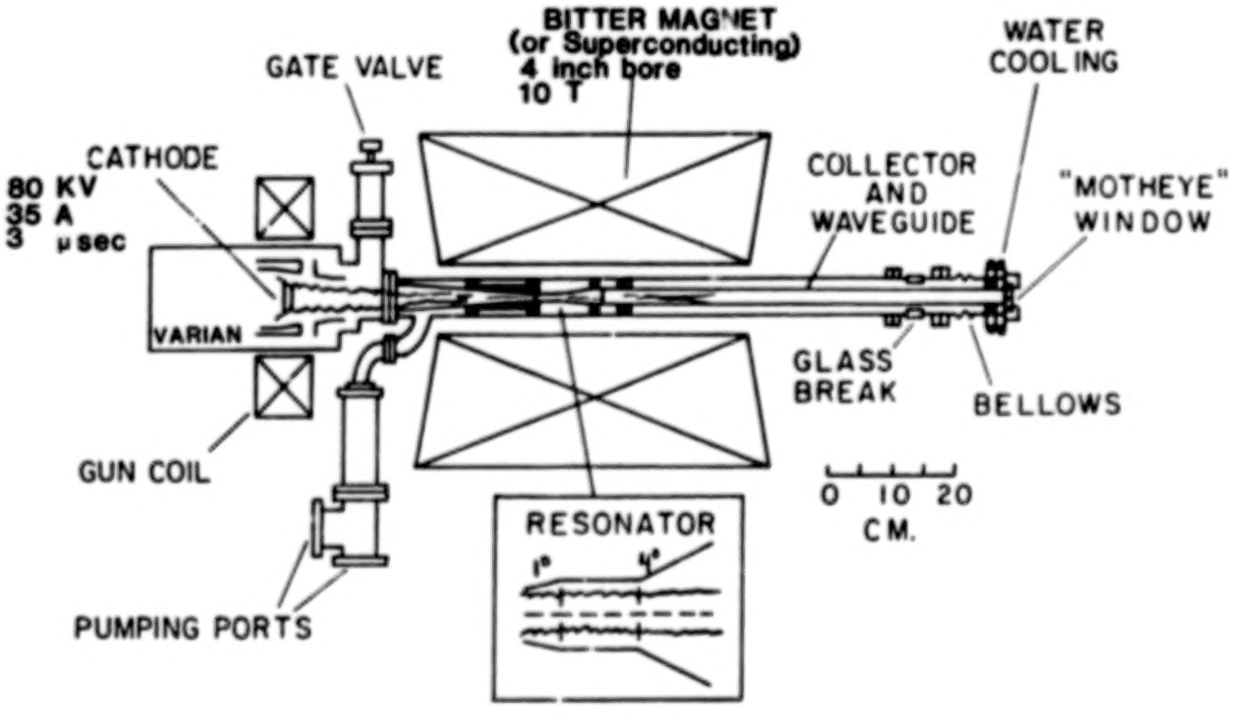
- HIGH EFFICIENCY
  ENERGY RECOVERY NOT REQUIRED.

- SIMPLE DEVICE CONFIGURATION

- BASIC PHYSICS UNDERSTOOD
  EFFICIENCY, FREQUENCY, SPACE CHARGE, INSTABILITIES.

SCHEMATIC OF EXPERIMENT

(MIT Gyrotron by K. Kreischer & R. Temkin)



MW GOALS

- EXTRAPOLATE 200 kW RESULTS TO MW POWER LEVELS
  - SINGLE CAVITY WITH ISOLATED, ASYMMETRIC MODE
- DETERMINE IF FOLLOWING ARE POSSIBLE:
  - SINGLE MODE EMISSION IN HIGHLY OVERMODED CAVITY
  - BEAM PROPAGATION NEAR I_{MAX}
  - BEAM-rf SEPARATION AFTER CAVITY
  - CONVERSION TO POLARIZED, GAUSSIAN BEAM
- STUDY ADVANCED CAVITY CONCEPTS
  - COAXIAL CAVITY
  - COMPLEX CAVITY
  - GYROKLYSTONS
- DEVELOP PHYSICS BASE FOR NEXT GENERATION OF GYROTRONS
  - 5-10 MW AT 140 GHz
  - 1 MW AT 280 GHz FOR CIT

GYROTRON DESIGN THEORY

- Linear theory: Starting current
- Nonlinear theory: Efficiency $\eta_\perp(F,\mu)$

  F=normalized rf field amplitude

  μ=normalized length
- Cavity ohmic losses sets upper limit on F
- Energy balance equation:

$$Q=4\pi\left(\frac{L}{\lambda}\right)^2$$

- Combining these equations yields:

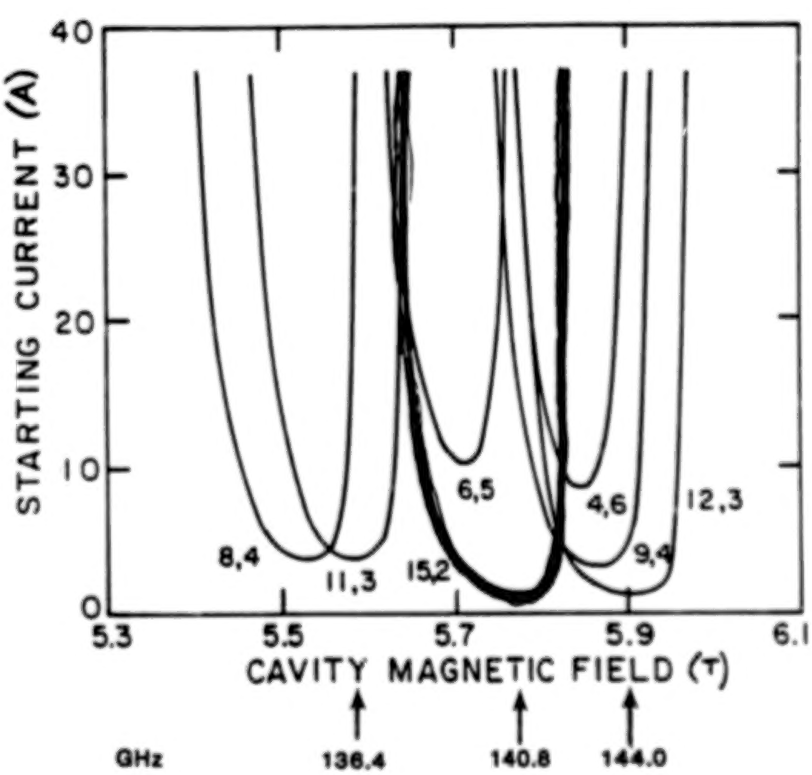
$$(\nu_{mp}^2 - m^2) = \frac{2470\mu\beta_\parallel P(\mathrm{MW})\nu^{2.5}(\mathrm{GHz})}{\beta_\perp^2\rho_{ohm}(\mathrm{W/m^2})}$$

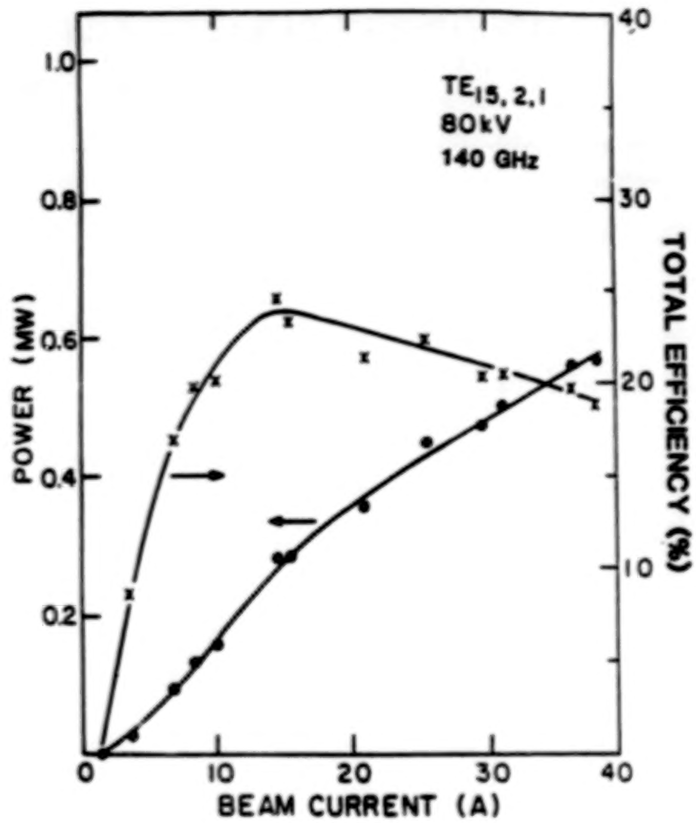
where cavity diameter $D/\lambda = \nu_{mp}/\pi$

- Others: Maximum Current
  Beam Mirroring
  Space Charge
  Beam Thickness
  Voltage Depression

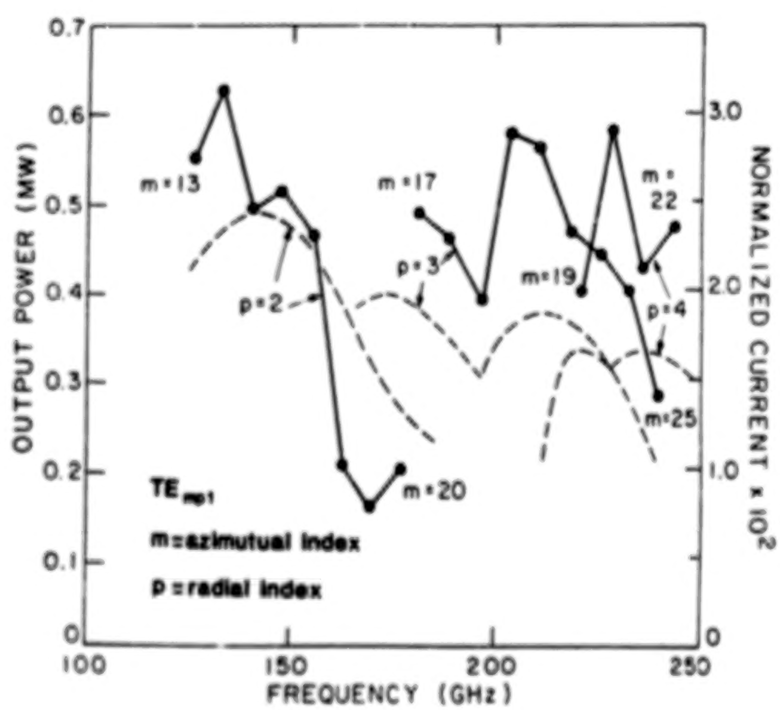
1 MW DESIGN PARAMETERS

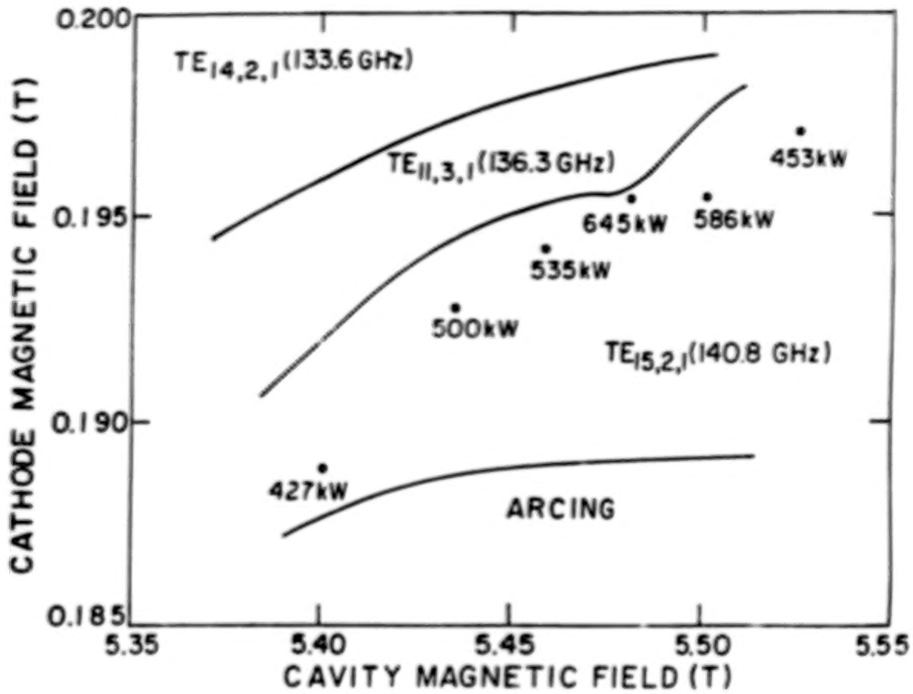
	140 GHz	280 GHz
Current(A)	35	42
Voltage(kV)	80	80
η_T(%)	36	30
Velocity ratio	1.93	2.0
Beam radius(cm)	0.53	1.4
Cavity radius(cm)	0.75	1.7
Cavity length(L/λ)	6.0	7.1
Diffractive Q	450	630
Magnetic compression	30	40
Cavity current density(A/cm^2)	384	510
Beam thickness(r_L)	3.85	3.2
Voltage depression(%)	4.0	2.6
Emitter radius(cm)	2.89	8.9
Mode	$TE_{15,2,1}$	$TE_{80,4,1}$
Mode separation(GHz)	7.2	3.0



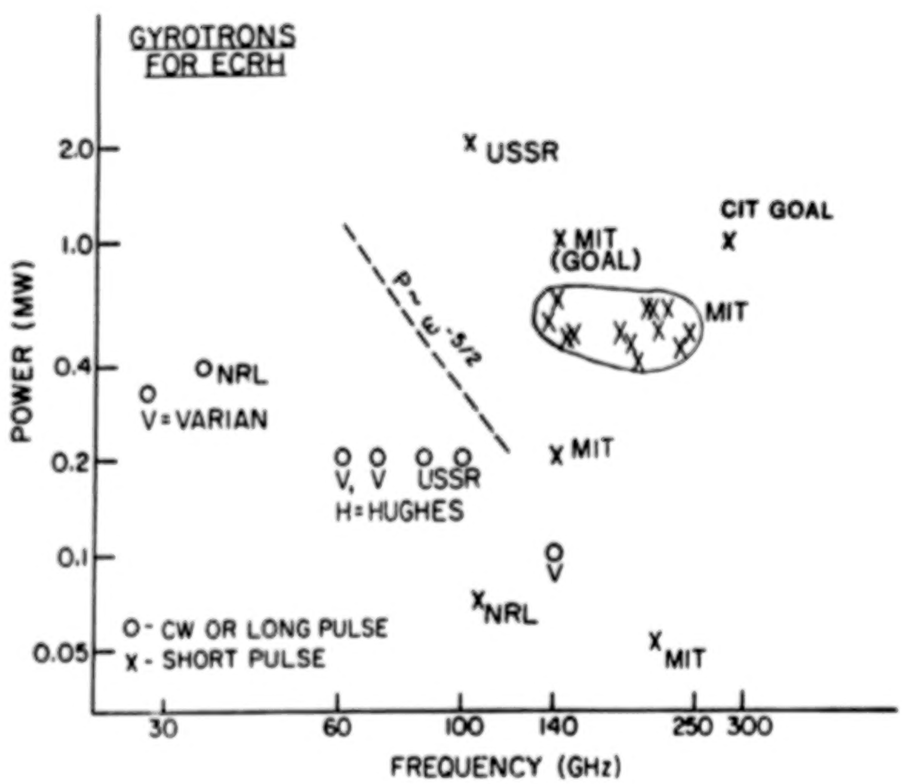


STEP TUNING
(Experimental Results)





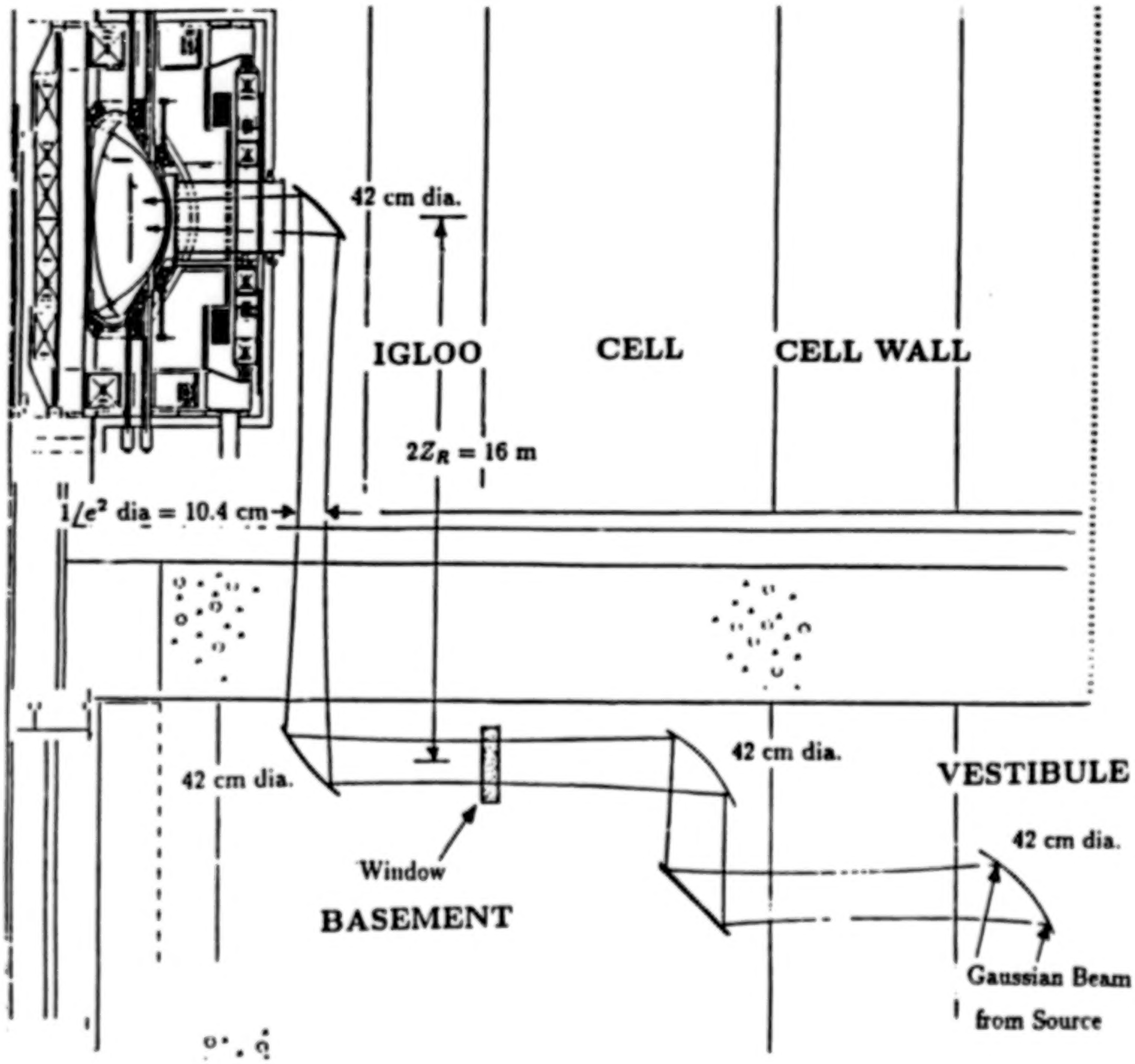
0.200
0.195
0.190
0.185
5.35
5.40
5.45
5.50
5.55
CATHODE MAGNETIC FIELD (T)
CAVITY MAGNETIC FIELD (T)
TE14,2,1 (133.6 GHz)
TE11,3,1 (136.3 GHz)
TE15,2,1 (140.8 GHz)
453kW
645kW
586kW
535kW
500kW
427kW
ARCING



GYROTRONS FOR ECRH
POWER (MW)
FREQUENCY (GHz)
2.0
1.0
0.4
0.2
0.1
0.05
30
60
100
140
250
300
X USSR
CIT GOAL
X MIT (GOAL)
MIT
P ~ ω -5/2
O NRL
V = VARIAN
V, V USSR
H = HUGHES
X MIT
V
X NRL
X MIT
O - CW OR LONG PULSE
X - SHORT PULSE

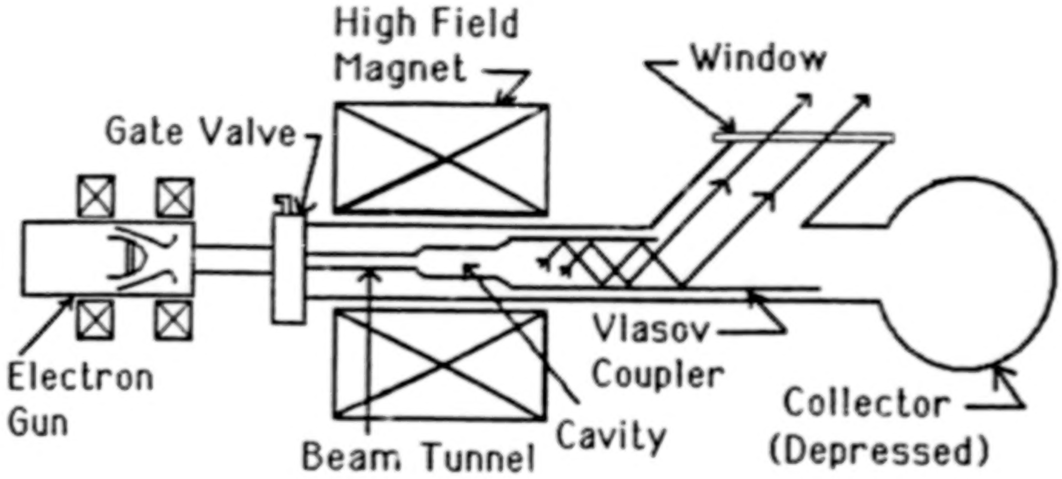
COMPACT IGNITION TOKAMAK (10 MW, 280 GHz, CW)

P. Woskov, ECH/CIT, 1987 (MIT)



Possible CIT 280 GHz Optical Transmission Line

GYROTRON WITH QUASI-OPTICAL OUTPUT COUPLER



120 GHz Designs

(1 MW, 10 MW Gyrotrons)

Power(MW)	1.0	10.0
Current(A)	29	240
Voltage(kV)	80	90
η_T(%)	43	46
Velocity Ratio	2.0	2.5
Wall Loading(kW/cm^2)	1.6	2.0
Beam Radius(cm)	0.62	1.8
Cavity Radius(cm)	0.88	1.87
Maximum Current(A)	62	560
Cathode Current Density(A/cm^2)	5	10
Beam Thickness(mm)	0.21	0.30
Cavity Length(cm)	1.33	0.98
Diffractive Q	370	193
Voltage Depression (%)	**3.5**	**8.4**
J_s(A/cm^2)	**1150**	**1250**
J(A/cm^2)	**350**	**700**

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10-100 kW SUBMILLIMETER GYROTRON

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High Frequency
High Harmonic Gyrotrons

$[\ \omega - \kappa_z v_z = N\omega_c\ ;\ \ N = 1, 2, 3, 4, 5 \ldots\ ]$

- Generalized nonlinear theory applied to gyrotrons for second through fifth harmonics.

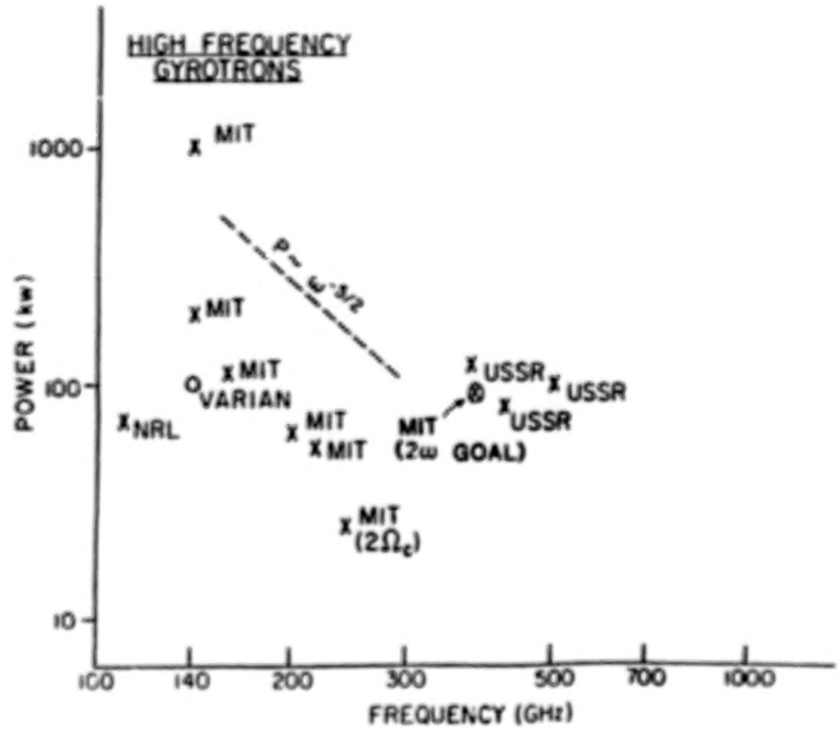
- Numerical results for efficiency over a wide range of normalized paramenters have been obtained.

- High maximum efficiencies have been obtained:

Harmonic (N)	$\eta_{\perp\ max}$
2^{nd}	70%
3^{rd}	55%
4^{th}	45%
5^{th}	37%

- Results allow optimization of design of high harmonic gyrotrons.

- Reduced B–field required or go to higher wavelengths (ω, submillimeter).



Observed Second Harmonic Emission

65 kV, 3 A

B (T)	Mode	Frequency (GHz)	Power (kW) ±2 kW
8.40	$TE_{10,3,1}$	417.1	14
7.56	$TE_{16,1,1}$	372.6	3
7.41	$TE_{8,3,1}$	366.9	4
7.38	$TE_{11,2,1}$	363.3	7
6.88	$TE_{10,2,1}$	339.3	4
6.66	$TE_{14,1,1}$	329.6	5
6.14	$TE_{3,4,1}$	301.6	4

Gyrotron Results
Summary

- 750 kW, 140 GHz in 3 μs pulsed operation; 80 kV, 35 A.
- 500 kW step tunable from 140 – 250 GHz.
- 15 kW at 420 GHz at second harmonic.
- 100 kW, 140 GHz CW operation at Varian.

M. I. T.
CARM AMPLIFIER
PROGRAM

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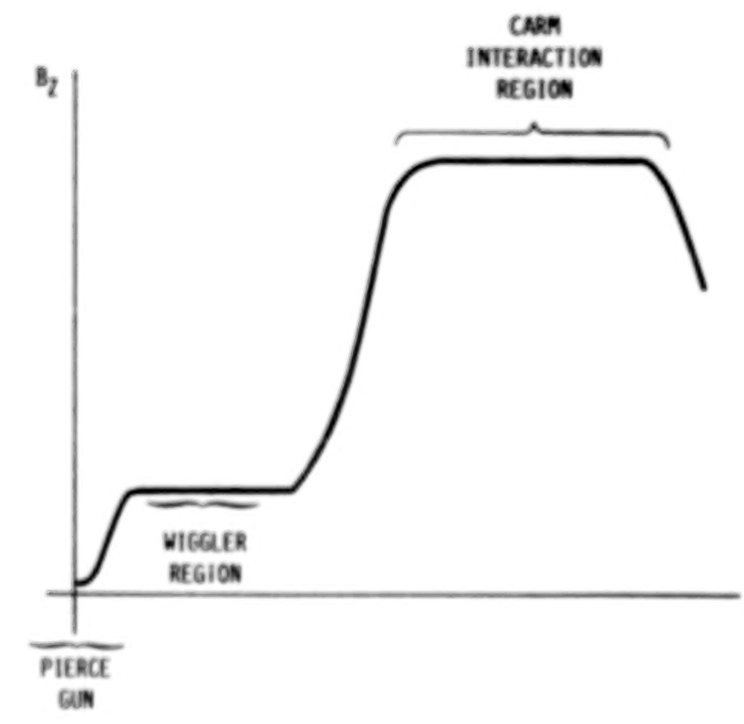
CARM AMPLIFIER EXPERIMENT AT M.I.T.

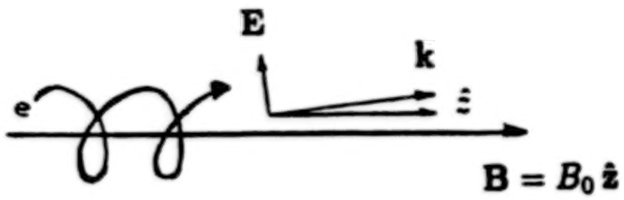
- 140 GHz AMPLIFIER EXPERIMENT
- TE_{11} OR TE_{12} MODE
- 450 kV PIERCE GUN (PHASE I)
- 700 kV, 50 A ELECTRON BEAM FROM PIERCE GUN (PHASE II)
- $\beta_{\perp}/\beta_{\parallel}$ PRODUCED ON BEAM BY WIGGLER



○ INTRODUCTION

- Cyclotron Autoresonace Maser (CARM) also known as Doppler-Shift Dominated Cyclotron Resonance Maser or the Wiggler-Free Free-Electron Laser.

- Basic Configuration:



- Resonance Condition:

$$\omega - k_{\parallel}v_{\parallel} = \frac{\omega_{c0}}{\gamma}$$

where $\omega_{c0} = eB_0/mc =$ cyclotron frequency.

- Doppler shift term large for CARM.

- Define $\beta_{ph} = v_{ph}/c = \omega/ck_{\parallel} =$ wave phase velocity.

$$\beta_{ph} \sim 1 \Rightarrow \textbf{CARM}$$

$$\beta_{ph} \rightarrow \infty \Rightarrow \textbf{GYROTRON}$$

$$\omega = \frac{\omega_{c0}}{\gamma(1 - \beta_{\parallel}/\beta_{ph})}$$

○ CARM Autoresonance Condition

- **For single electron emitting photon:**

$$\Delta E = \hbar\,\omega$$

$$\Delta p_{\|} = \hbar\,k_{\|}$$

$$\Rightarrow \frac{\Delta E}{\Delta p_{\|}} = \frac{\omega}{k_{\|}} = \beta_{ph}\,c = \text{const.}$$

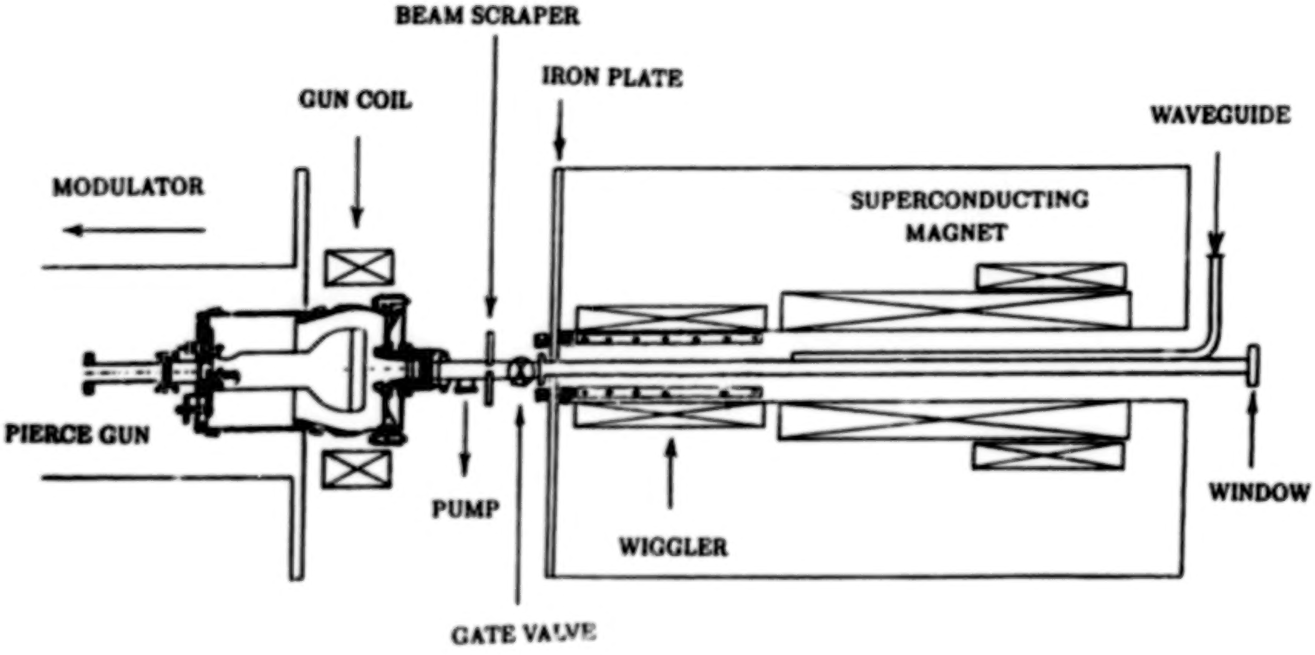
$$\Rightarrow \Delta\left(\gamma_0 - \gamma_0\,\beta_{\|0}\,\beta_{ph}\right) = 0$$

- Constant of Motion: $\left(\gamma - \gamma\,\beta_{\|}\,\beta_{ph}\right)$
- Compare with resonance condition:

$$\omega = \frac{\omega_{c0}}{\gamma_0(1 - \beta_{\|0}/\beta_{ph})}$$

- For $\beta_{ph} = 1$, particles initially in resonance will remain in resonance as γ decreases. This is termed Autoresonance.
- At autoresonance, change in Doppler shift term is compensated by change in cyclotron resonance term. Azimuthal and axial bunching compensate each other.
- This constant of the motion is valid only for uniform amplitude EM fields.

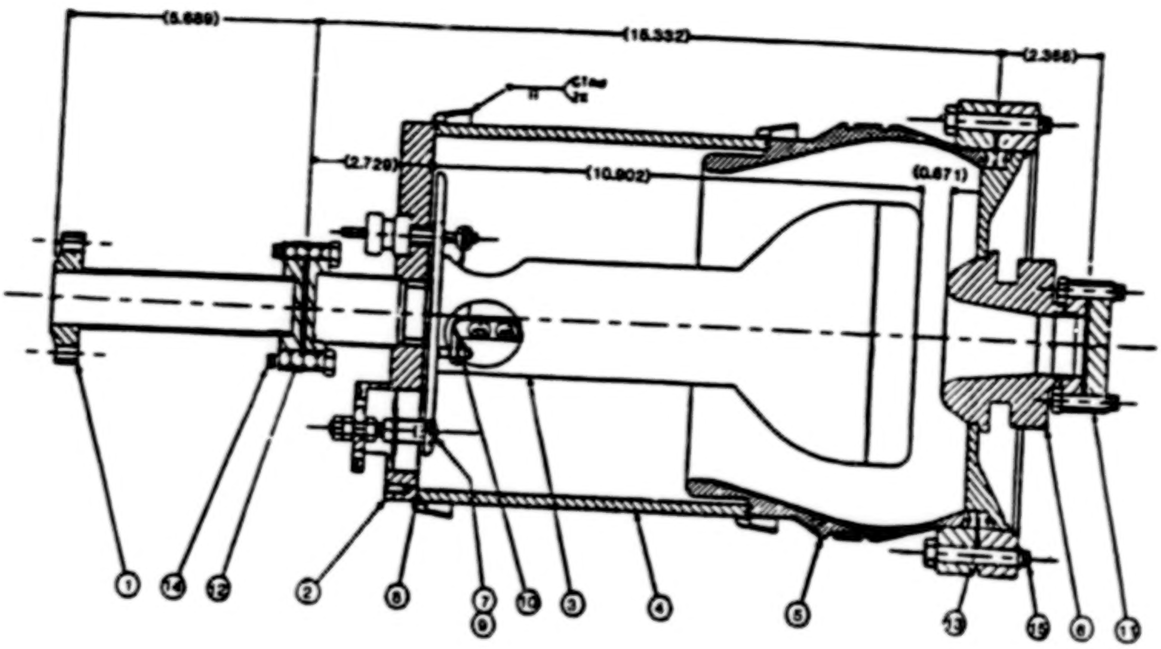
CARM AMPLIFIER SCHEMATIC

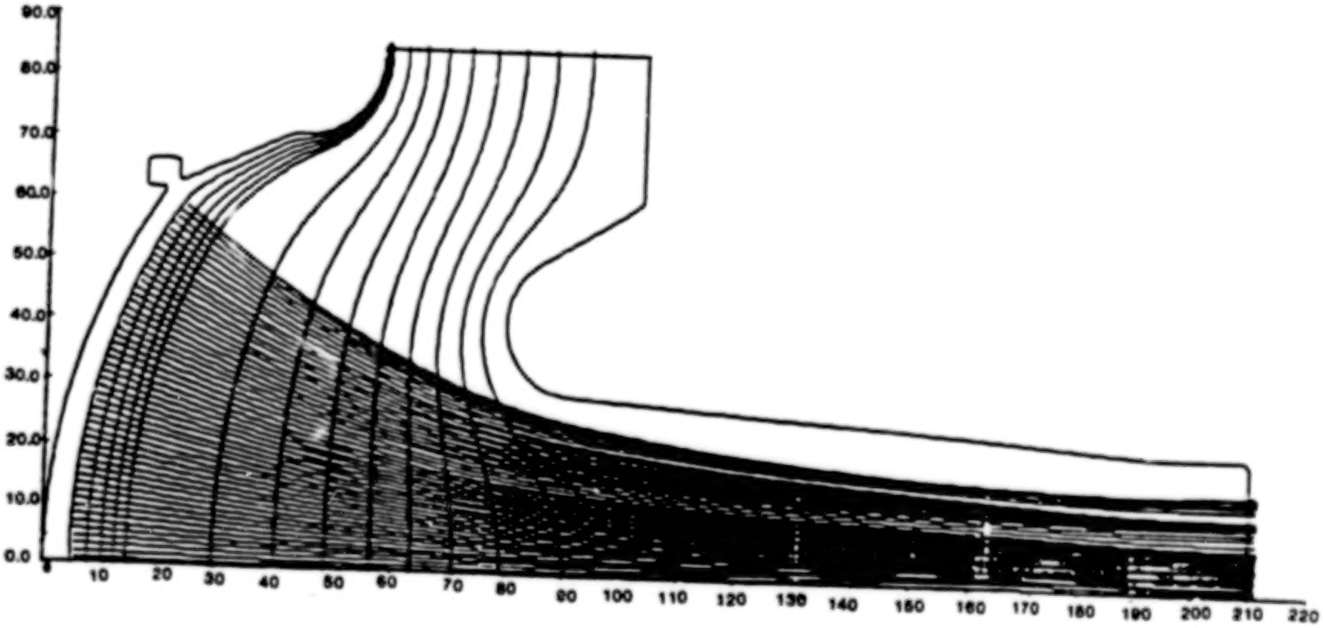


MIT ELECTRON GUN

450 kV, 600 A, 2 μP

(BUILT BY SLAC, STANFORD)



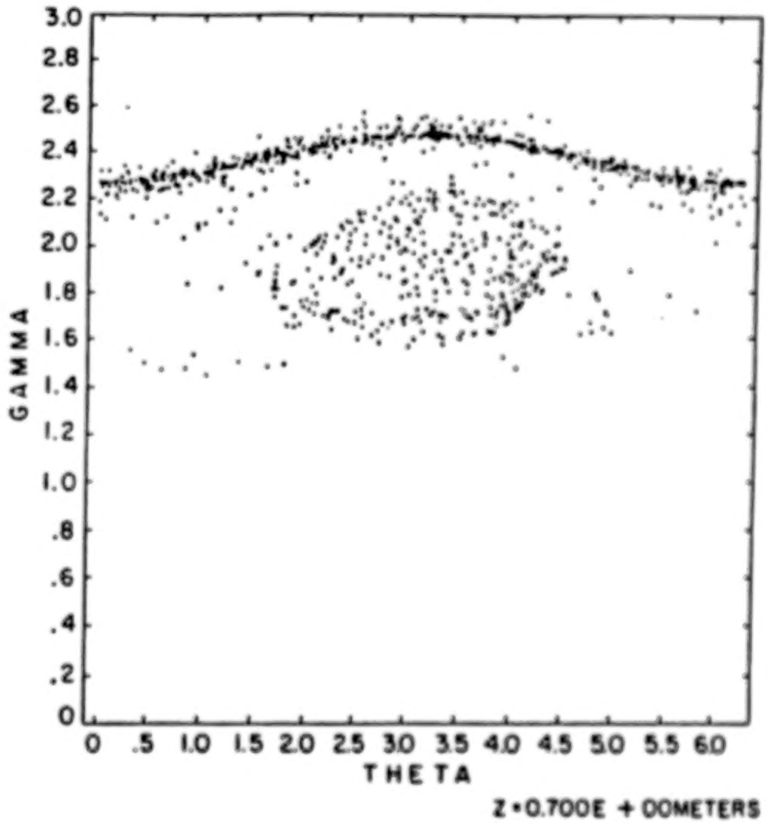


Baseline Design for 140 GHz CARM Amplifier
(700 kV Electron Gun)

Parameter	Design Value
Mode	TE_{11}
β_{ph}	1.066
$\beta_{\perp 0}/\beta_{\parallel 0}$	0.5 (variable)
a	1.8 mm
r_b	1.0 mm
Voltage	700 kV
Peak Current	50 A
Beam Quality ($\sigma_{\beta\parallel}/\beta_{\parallel}$)	1.0%
Peak Output Power	6.8 MW
Peak Input Power	~50 W
Efficiency	20 % (untapered)
B-Field	~ 2.64 T

Phase space of the CARM interaction with a tapered magnetic field

$\sigma_\gamma = 0.02$, $\sigma_{\beta\parallel} = 0.06$, $z_{tap} = 40$ cm



CONCLUSIONS

- GYROTRON HAS MADE VERY IMPRESSIVE ADVANCES IN LAST DECADE. INDUSTRIAL DEVELOPMENT AND RESEARCH.
- SCALING OF GYROTRONS TO HIGHER FREQUENCY AND POWER IS VERY PROMISING. NEW APPROACHES MAY BE NEEDED.
- 1 MW, 250 GHz CW GYROTRON APPEARS FEASIBLE. BASELINE DESIGN PRESENTED.
- HIGH PEAK POWER DEVICES (SUCH AS RELATIVISTIC GYROTRON) ARE ALSO PROMISING, BUT ARE NOT AS WELL UNDERSTOOD.

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SOLAR-PUMPED LASER FOR FREE SPACE POWER TRANSMISSION

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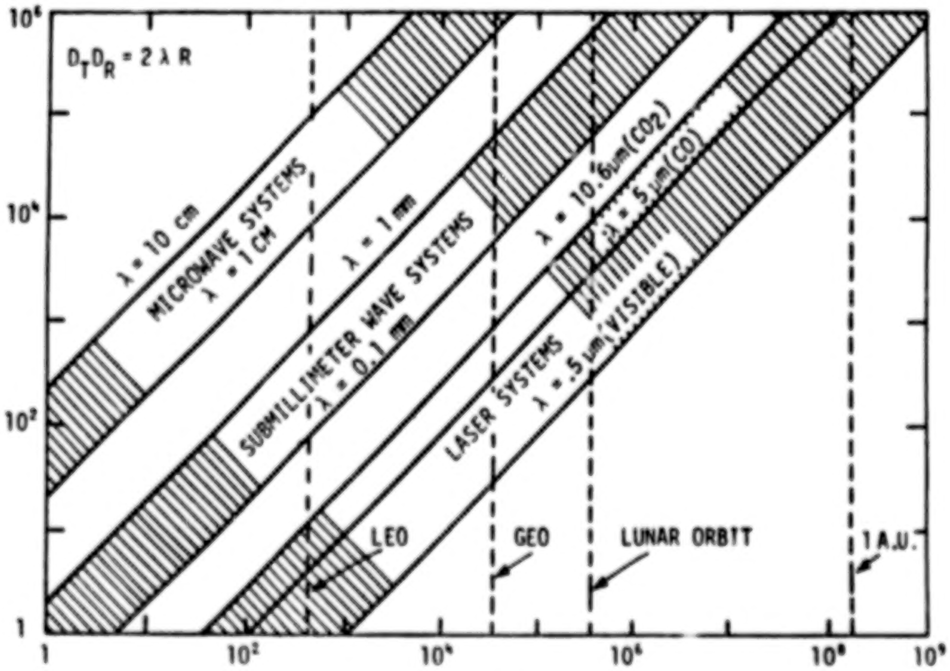
LASER POWER TRANSMISSION

- O LASER IS ONLY FEASIBLE SYSTEM FOR LONG RANGE (> $1{,}000_{KM}$) POWER TRANSMISSION IN SPACE.
- O LASER BEAM ACTS AS "SUPER CONDUCTOR" TO DELIVER HIGH GRADE POWER--NEAR ZERO ENTROPY.
- O MULTIMISSION SUPPORT POSSIBLE--ECONOMICAL.
- O LIGHT WEIGHT SYSTEMS IDENTIFIED-DIRECT SOLAR PUMPED LASERS AND LASER DIODE ARRAYS.

TRANSMITTER/RECEIVER SIZES vs RANGE



LASERS AVAILABLE FOR LASER POWER TRANSMISSION

O REQUIREMENTS

LASER POWER	> 10 MW	ORBITAL MANEUVERING	
	> 1 GW	EARTH-TO-ORBIT LAUNCHING (> 1 TON)	
	~ 1 MW	OTHER MISSIONS	
PHOTON FLUX	$< 2 \times 10^5$ W/cm^2		CW
	$< 2 \times 10^7$ W/cm^2		PULSED (LSD PROP.)
WAVELENGTH	> 10 μm	THROUGH ATMOSPHERE	
	~ 1 μm	DEPENDS ON THE POWER RECEIVERS IN FREE SPACE	
PULSE WIDTH	50 ns - 1 μs	PLASMA GEN. AND HEATING	
EFFICIENCY	HIGH	TRANSMITTER AND RECEIVER	

O GROUND BASED WITH SPACE RELAY

FREE ELECTRON LASER (PULSED), CO_2 LASER (CW)

STATE-OF-THE-ARTS: MULTI-KILOWATT (CW), 500 kJ (PULSED)

SCALING-UP: POSSIBLE TO MULTI-MW LEVEL.

O TECHNICAL ISSUES:

MANY ORDERS OF MAGNITUDE UP-SCALING NEEDED

ATMOSPHERIC INTERFERENCE

SPACEBORNE LASER OPTION SHOULD BE CONSIDERED

SPACE-BORNE LASERS FOR POWER TRANSMISSION

O SOLAR POWERED LASERS

DIRECT SOLAR PUMPED LASERS

IODINE PHOTODISSOCIATION LASER, IBr PHOTODISSOCIATION LASER

SOLID STATE LASERS (Nd^{3+}), LIQUID Nd^{3+} LASERS, DYE LASERS

INDIRECT SOLAR PUMPED LASERS

N_2-CO_2 BLACKBODY PUMPED LASER, CO BLACKBODY PUMPED LASER

SOLAR PHOTOVOLTAIC POWERED

ELECTRIC DISCHARGE LASERS (EXCIMER, COPPER, CO_2)

DIODE LASER ARRAYS/DIODE LASER PUMPED LASERS.

O NUCLEAR POWERED LASERS

DIRECT NUCLEAR-PUMPED LASERS

HIGH EFFICIENCY ELECTRIC DISCHARGE LASERS OR DIODE LASERS

SOLAR PHOTOVOLTAIC ELECTRICALLY PUMPED ONE MW LASER SYSTEMS

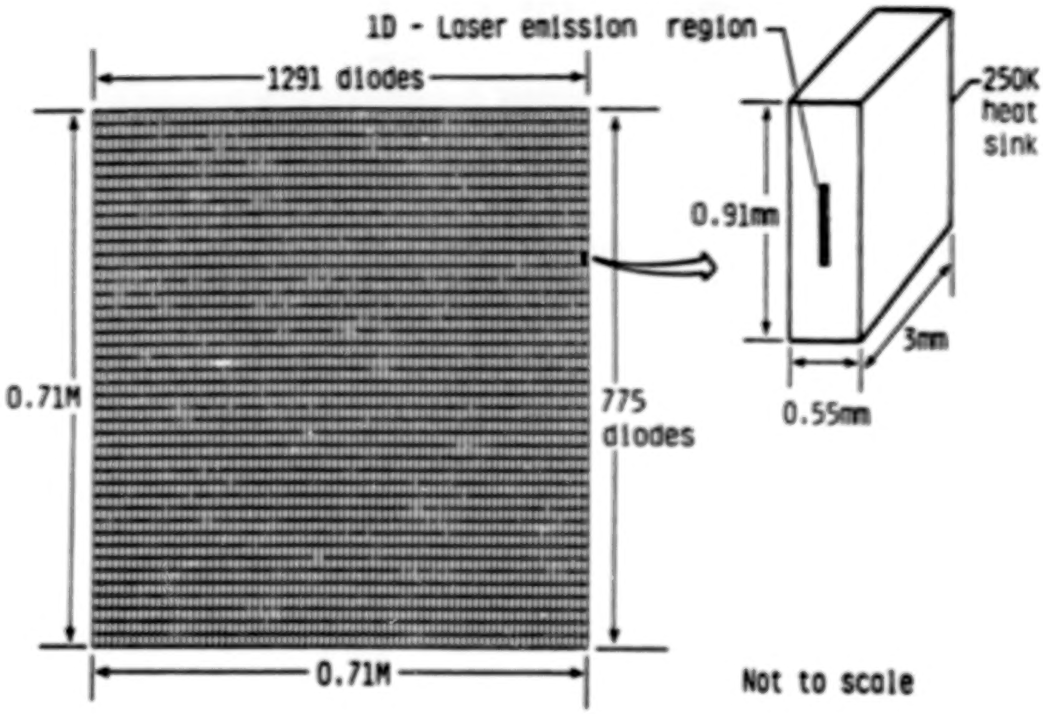
		KrF EXCIMER	COPPER VAPOR	DIODE ARRAY	CO_2	REMARKS
LASER WAVELENGTH	μm	0.248	0.510 0.570	0.8	10.6	
INTRINSIC EFFICIENCY	%	10	3	30	13.7	
ELECTRIC EFFICIENCY	%	2.5	1.4	30	5.5	WALL-PLUG EFF.
SOLAR TO LASER EFFICIENCY	%	0.40	0.24	6.0	0.88	
SOLAR POWER COLLECTED	MW	250	412	16.5	113.5	
ELECTRIC POWER FROM PV ARRAY	MW_E	50	82	3.3	22.7	20 PERCENT EFFICIENCY
SOLAR PANEL AREA	m^2	185,185	305,185	12,318	84,444	1.35kW/m^2 AM0
THERMAL RADIATED POWER	MW	49	81	2.3	21.7	OTHER THAN SOLAR ARRAY
RADIATOR TEMP./AREA	K/1000m^2	300/21.8 373/27.3 326/14.1	300/107 1770/.057	250/10.4	300/9.8 409/10.8	
	TOTAL	63.2	107.057	10.4	20.6	

SOLAR PHOTOVOLTAIC PUMPED ONE MW LASER SYSTEMS

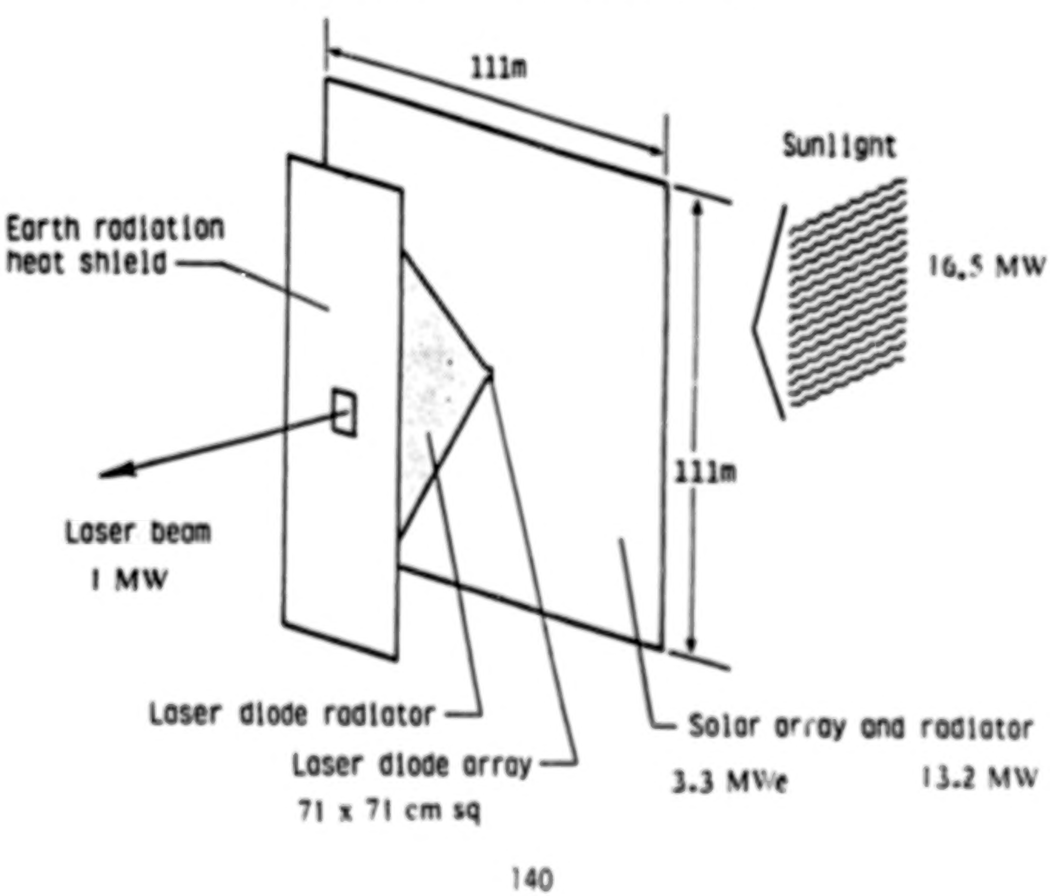
		KrF EXCIMER	COPPER VAPOR	DIODE ARRAY	CO_2	REMARKS
ELECTRIC EFFICIENCY	%	2.5	1.4	30	5.5	AFTER POWER CONDITIONING
ELECTRIC POWER	MWe	50	82	3.3	22.7	
SOLAR PANEL AREA, MASS	m^2 KG	185,185 166,666	305,185 273,333	12,318 11,000	84,444 76,000	20% EFFICIENCY 300 W/KG (REF. 1)
POWER CONDITIONER	KG	88,000	144,320	5,808	40,120	1.76 KG/kWe (REF. 2)
THERMAL POWER RADIATED	MW	49	81	2.3	21.7	
RADIATOR AREA MASS	m^2 KG	63,200 170,640	107,057 289,054	10,400 28,080	20,600 55,620	2.7 KG/m^2 (REF. 3)
TOTAL MASS	KG	425,306	706,707	44,888	171,740	LASER CAVITY MASS NOT INCLUDED

REF. 1 - E. A. GABRIS AND A. D. SCHNYER, PROC. 22ND IECEC AUG 1987, P. 33
2 - J. A. MARTIN AND L. WEBB, PROC. 22ND IECEC AUG 1987, P. 321
3 - E. P. FRENCH, 15TH IECEC, 1980, P. 394.

2D LASER DIODE ARRAY



1MW LASER DIODE ARRAY SYSTEM



LASER DIODE ARRAY TECHNICAL ISSUES

ADVANTAGES:

- O HIGH SYSTEM EFFICIENCY (6%)
- O SMALL AND POTENTIALLY LEAST MASSIVE SYSTEM
- O NO LASANT FLOW REQUIRED
- O REASONABLE LASER WAVELENGTH
- O LASER DIODE ARRAY HAS GOOD POWER COUPLING TO SOLAR ARRAY
- O LOW WEIGHT/SIZE WASTE HEAT RADIATOR

DISADVANTAGES:

- O LOW TEMPERATURE LASER OPERATION REQUIRES LOW T RADIATOR AND HEAT REMOVAL SUBSYSTEM
- O VERY TEMPERATURE SENSITIVE
- O EFFECTS OF SPACE RADIATION MAY BE SEVERE

TECHNICAL ISSUES:

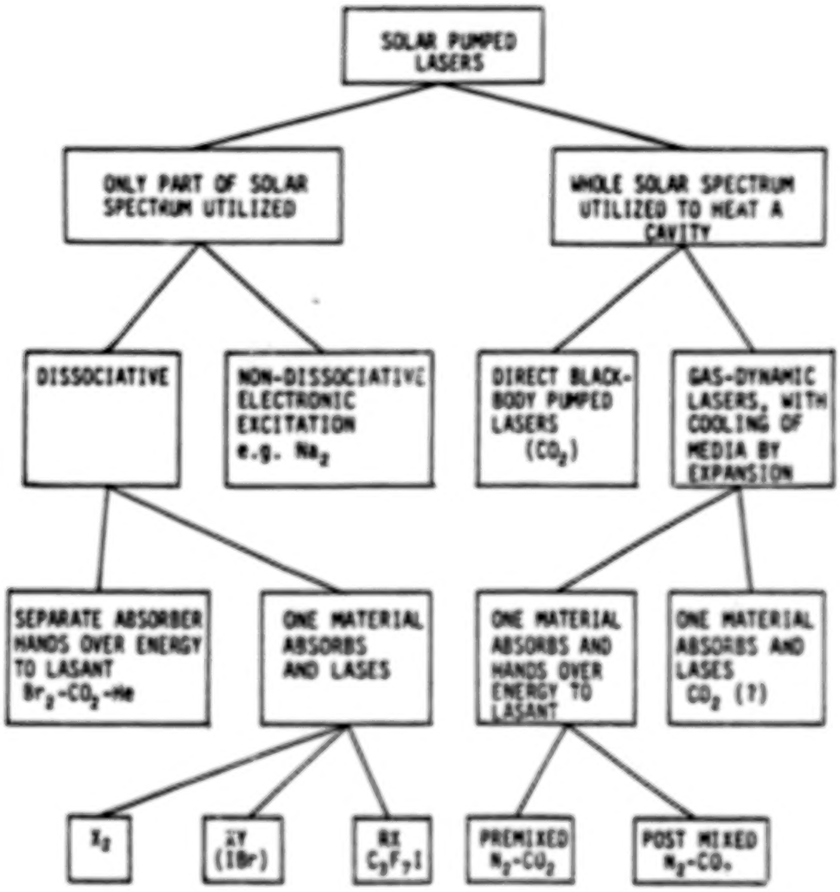
- O PHASE MATCHING ENTIRE LASER ARRAY NOT DEMONSTRATED
- O SCALING PRESENT 1-WATT SINGLE DIODES TO 1MW DIODE ARRAY
- O ARRAY COOLING WITH HEAT PIPES
- O ELECTRICAL DIODE LASER NETWORK

WEIGHT ESTIMATE OF DIODE PUMPED Nd YAG LASER SYSTEM

DIODE LASER EFFICIENCY	= 30%
PUMPING EFFICIENCY	= ND:YAG LASER OUTPUT/DIODE LASER INPUT
	= 35% (REF.)
ELECTRIC EFFICIENCY	= 10.5%
SOLAR DIODE LASER EFFICIENCY	= 6%
OVERALL SYSTEM EFFICIENCY	= .06 X .35 = .021 OR 2.1%
SOLAR POWER COLLECTED	= 1-MW/.021 = 48 MW
ELECTRIC POWER	= 48 MW X .20 = 9.6 MW_E
	6.72 (THERMAL) + 2.88 MW (LASER)
SOLAR PANEL AREA	35,477 m^2
WEIGHT	32,000 KG 300 We/KG
POWER CONDITIONING	16,896 KG 1.76 KG/KW_E
COOLING POWER	8.6 MW
RADIATOR TEMPERATURE	300 K/350 K
AREA	18,770 m^2
WEIGHT	50,680 KG 2.7 KG/m^2
TOTAL WEIGHT	99,576 KG

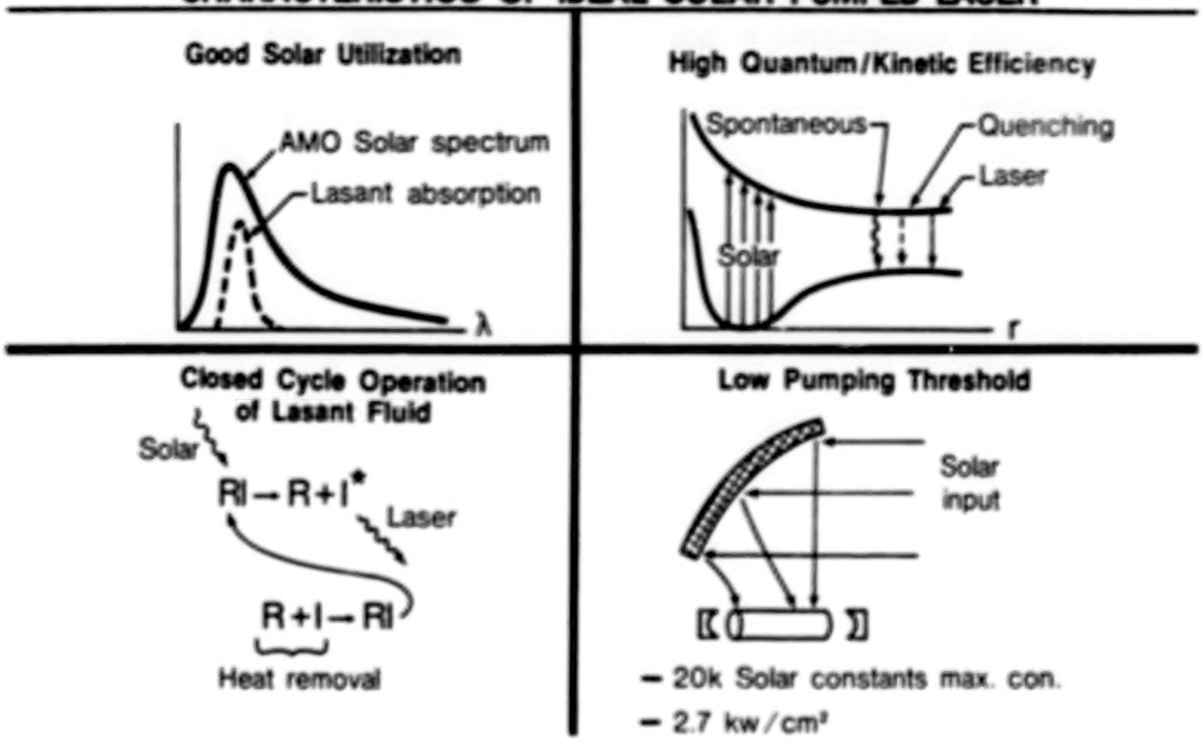
COMPARE: 44,888 KG FOR DIODE LASER ARRAY AND 30,270 KG FOR SOLAR IODINE LASER

VARIOUS SOLAR PUMPED GAS LASERS

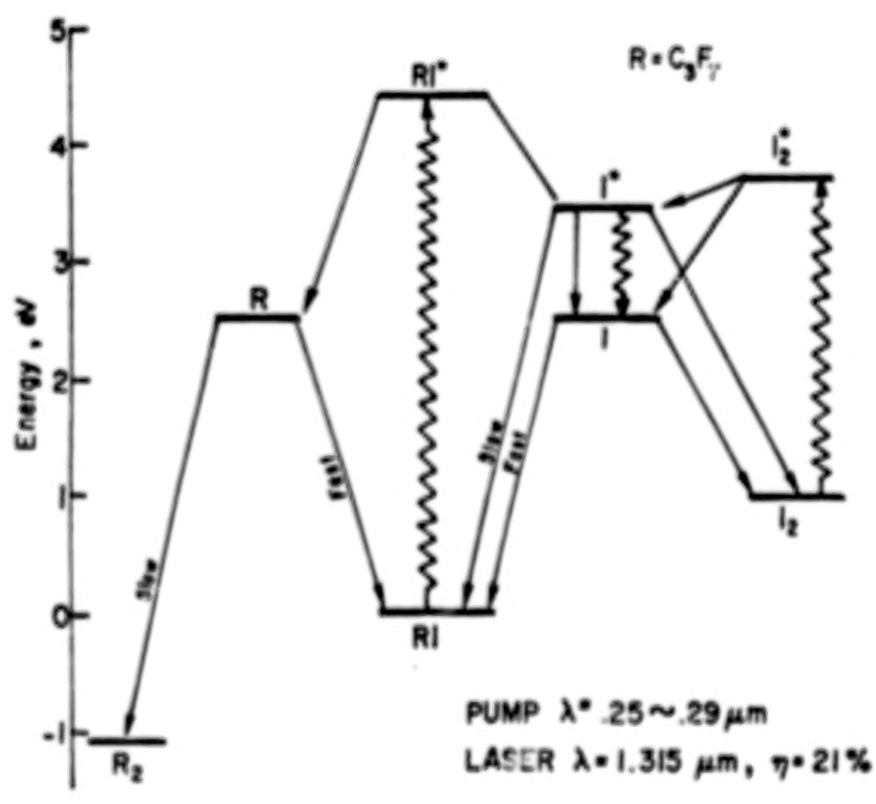


X = halogen, Y = different halogen atom
R = complex radical

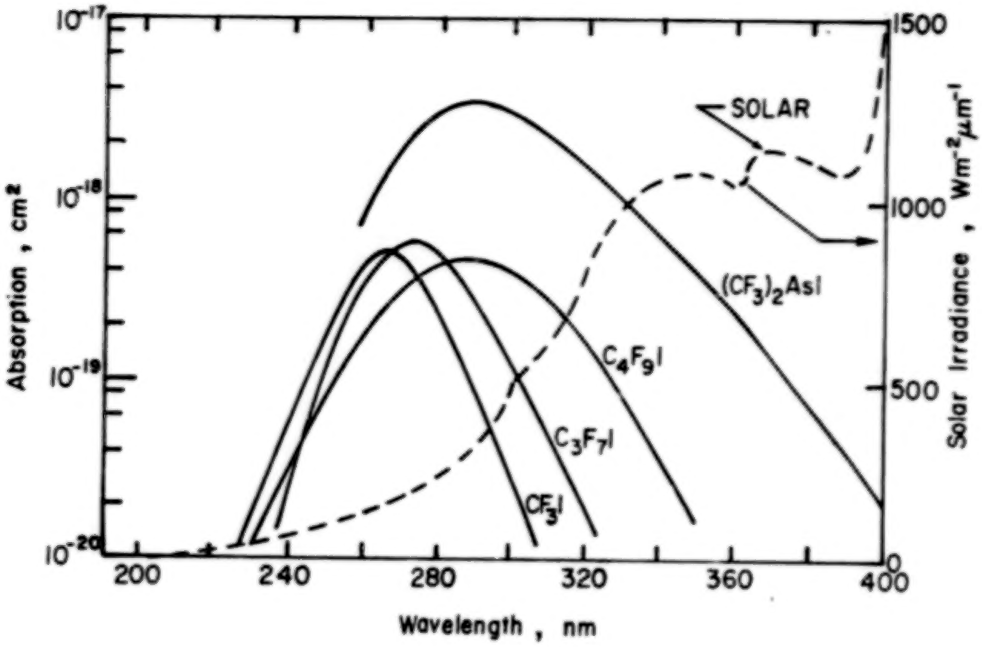
CHARACTERISTICS OF IDEAL SOLAR PUMPED LASER



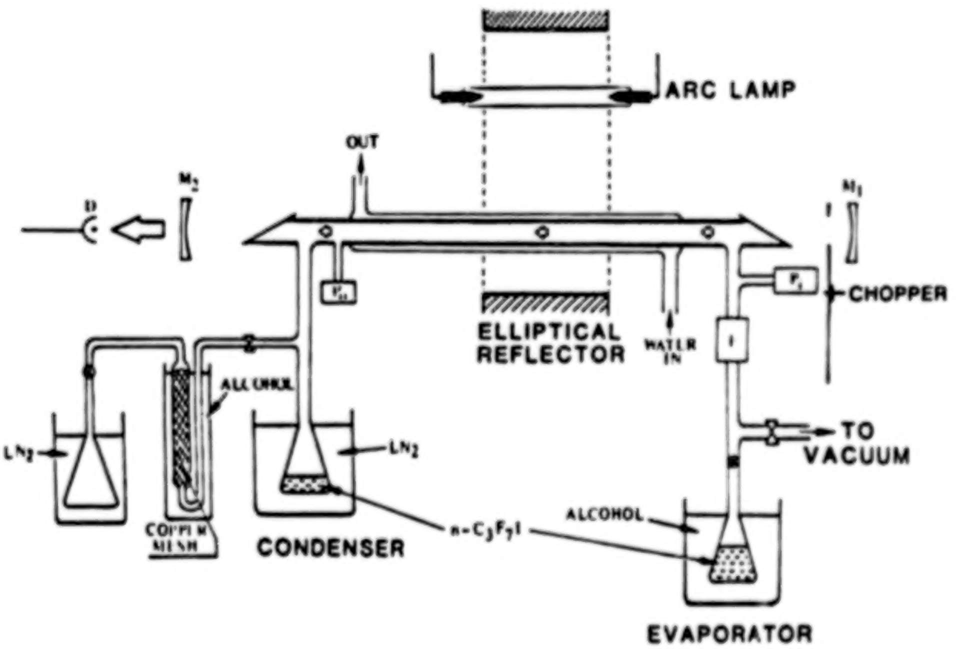
IODINE LASER KINETICS



ABSORPTION CROSS SECTIONS OF PERFLUOROALKYL IODIDES



SOLAR-PUMPED LASER EXPERIMENT



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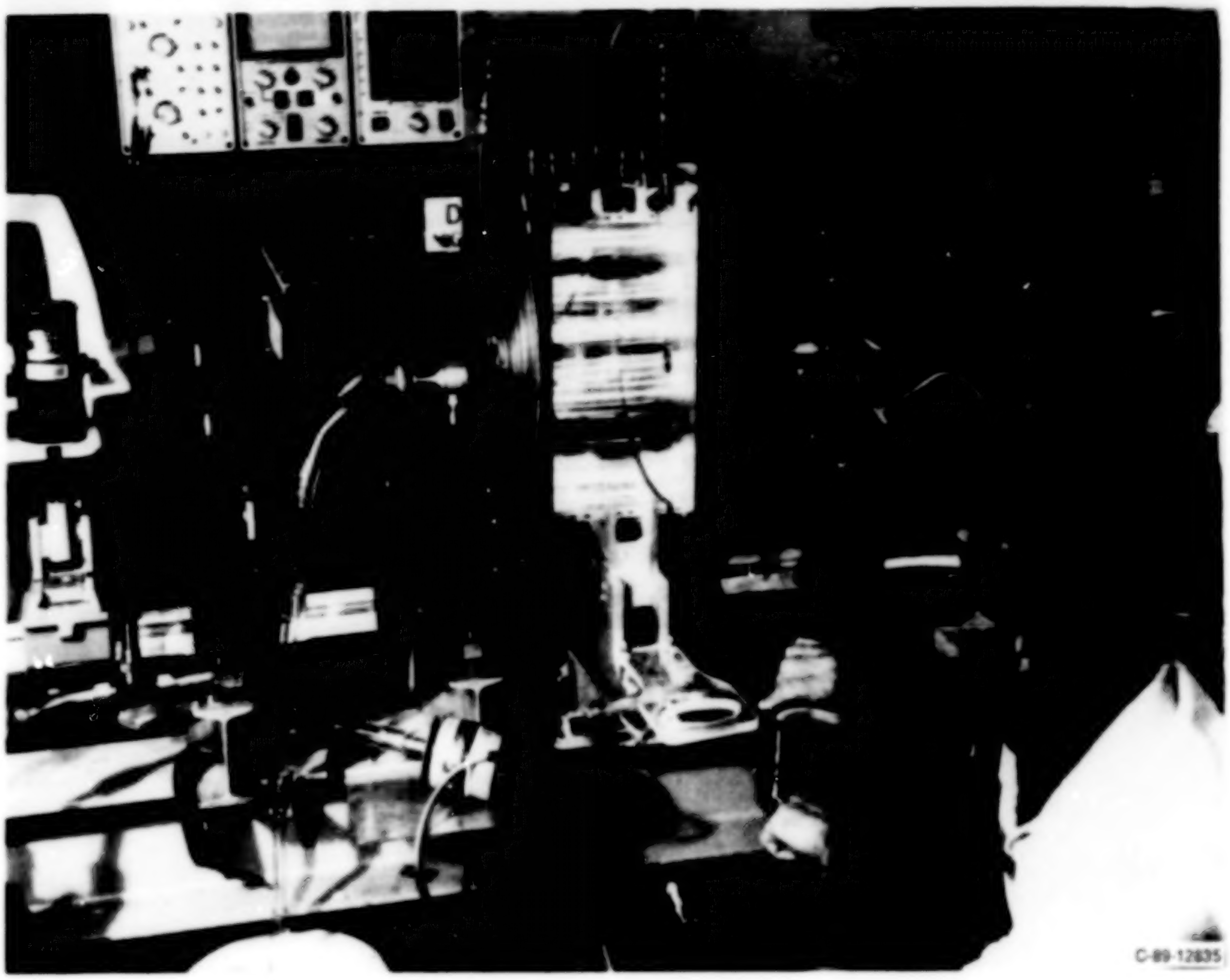
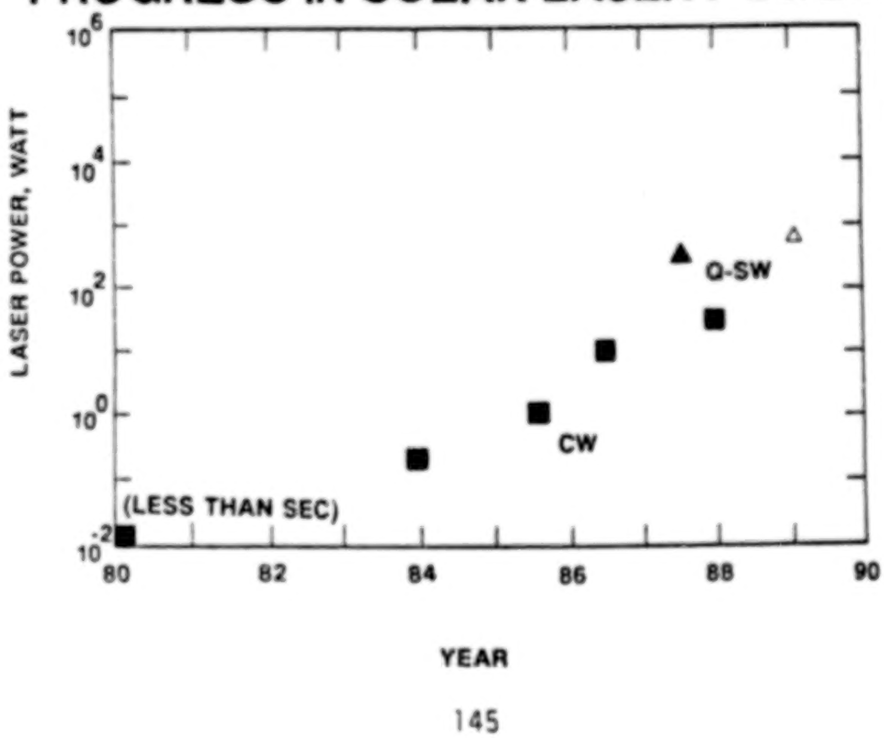
SOLAR SIMULATOR PUMPED IODINE LASER EXPERIMENT



PROGRESS IN SOLAR LASER POWER



STATUS OF SOLAR-PUMPED IODINE LASER

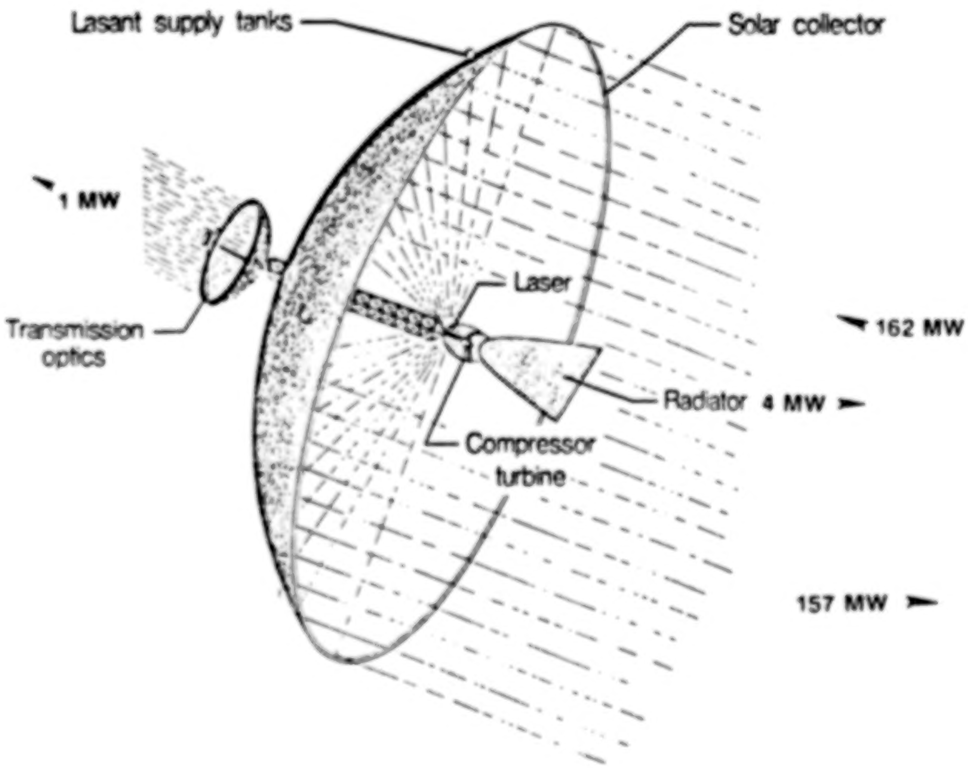
O KINETICS:	LASER MEDIUM	C_3F_7I, C_4F_9I
	99 PERCENT RECYCLABLE	
	PUMP BAND	250-290 nm NUV
	INTRINSIC EFFICIENCY	21 PERCENT
	EXCITATION MODE	PHOTODISSOCIATION TO I*
	SOLAR-TO-LASER EFFICIENCY	0.2 TO 0.6 PERCENT

O SCALABILITY: PULSED POWER > 2 TW/2 KJ ACHIEVED (MARX-PLANCK INT.)
CW > 15 W ACHIEVED (WITH SOLAR SIMULATOR)
SCALING NO THEORETICAL LIMIT, 1 GW LEVEL POSSIBLE
1MW SYSTEM STUDY COMPLETED

O SOLAR-SIMULATOR PUMPED LASER EXPERIMENT:
15 W CW, > 250 W PULSED (Q-SWITCHED)
FLOW, SUBSONIC
REP. PULSED MOPA UNDER DEVELOPMENT

O R & D ISSUES: LARGE SOLAR UV COLLECTOR
CHEMICAL REVERSIBILITY
BEAM PROFILE CONTROL
FLIGHT EXPERIMENT FOR THERMAL MANAGEMENT/BEAM TRANSMISSION

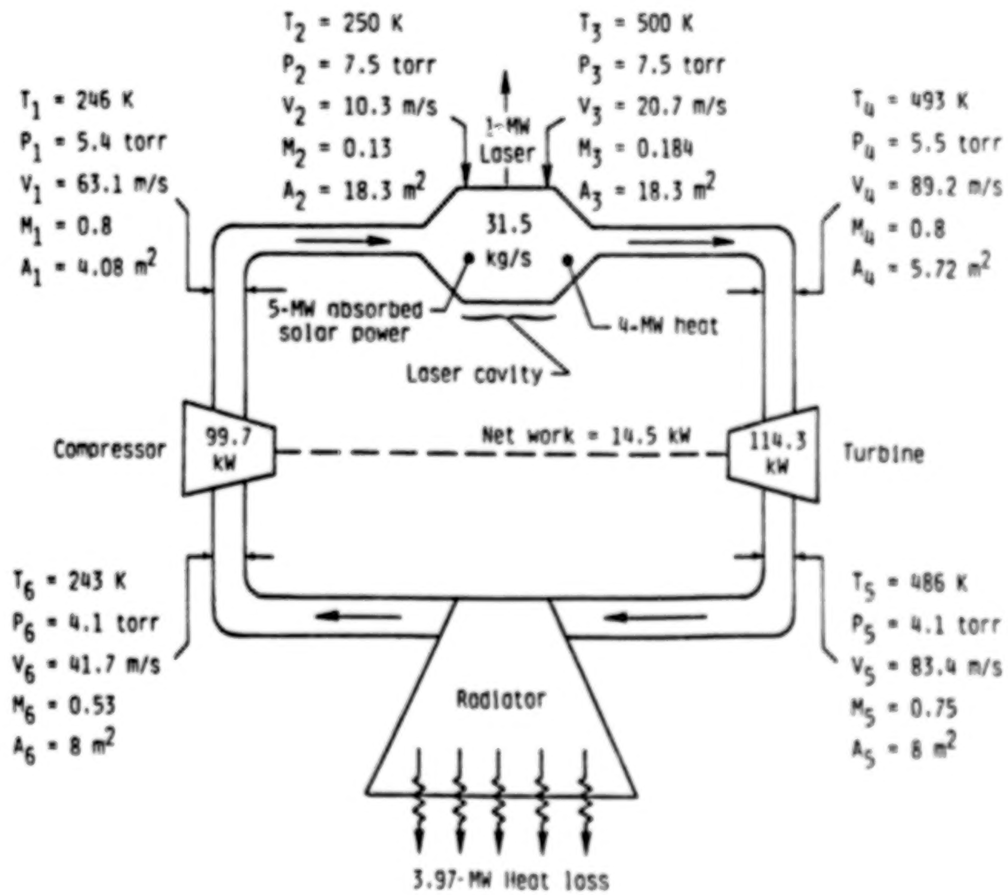
ONE MEGAWATT IODINE SOLAR PUMPED LASER POWER STATION



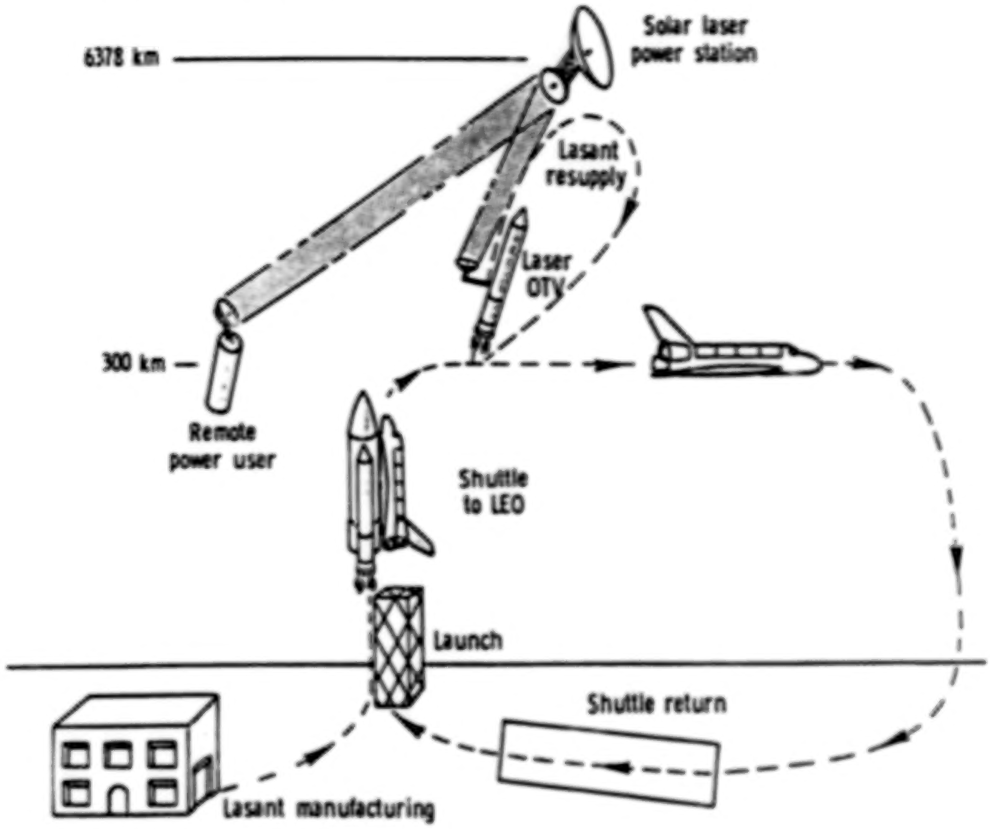
ONE MW SOLAR IODINE LASER SYSTEM MASS

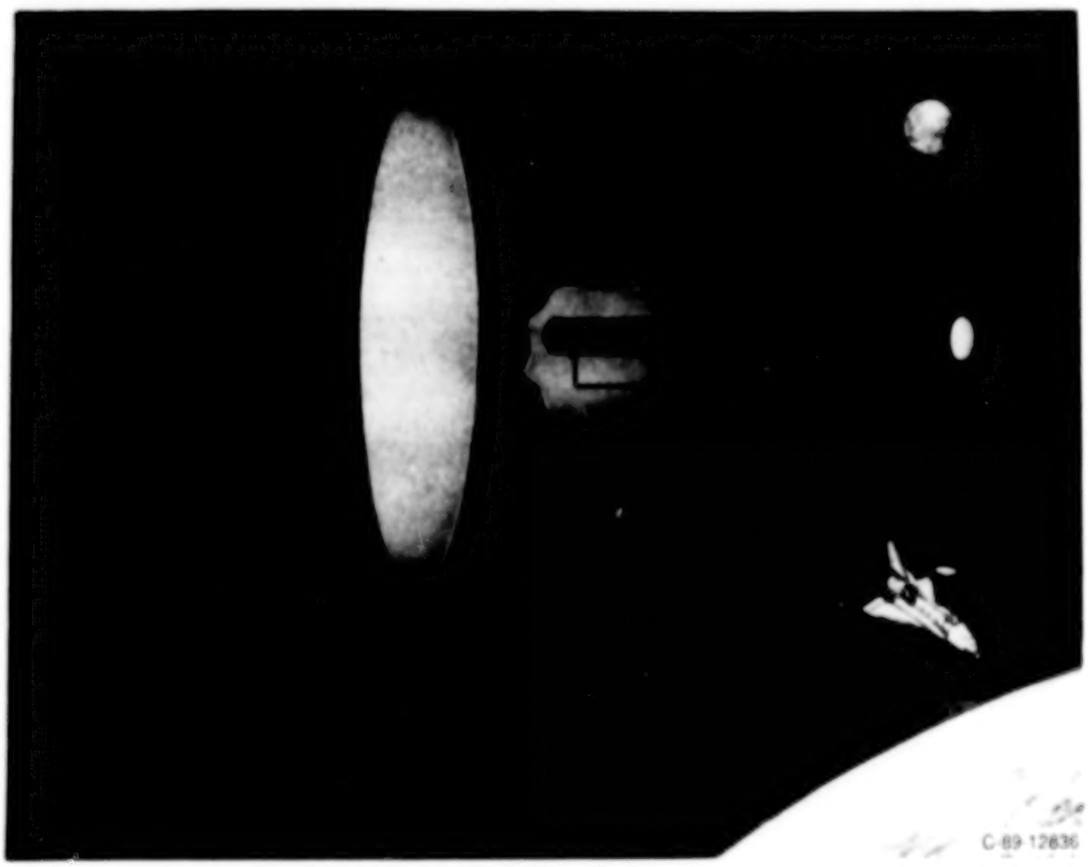
COLLECTOR, KG	14,800
RADIATOR, KG	15,470
TOTAL MASS FOR COLLECTOR AND RADIATOR, KG	30,270
OTHER SUBSYSTEMS:	
LASER CAVITY	
QUARTZ TUBE, KG	1,860
LASER CAVITY OPTICS, KG	1,000
LASER TRANSMISSION OPTICS AND STRUCTURE (27.6 M DIAM.), KG	24,000
GAS FLOW SYSTEM	
COMPRESSOR (2 STAGE), KG	12,700
TURBINE, KG	12,200
DUCTS, KG	3,000
T-C_4F_9I STORAGE TANKS (4 EMPTY TANKS), KG	270
ATTITUDE CONTROL SYSTEM (CMG AND FUEL)	
CMG, KG	2,000
150 KG FUEL/YR, KG	4,500

FLOW AND THERMAL CYCLES OF ONE MW IODINE LASER



OPERATION OF SOLAR PUMPED LASER POWER STATION





LASER POWER CONVERSION SYSTEMS

SYSTEM	EFFICIENCY
RECEIVER/PHOTOVOLTAIC/BATTERIES	34.0 %
RECEIVER/HEAT/BRAYTON/GENERATOR	34.2 %
RECEIVER/MHD GENERATOR	55.0 %
RECEIVER/PROPULSION (100 % THEORETICAL)	50.0 %

LASER POWER TRANSMISSION APPLICATIONS

- O VERY LOW EARTH ORBIT SATELLITE -- DRAG REDUCTION
- O OTV (LEO TO GEO) -- WEIGHT REDUCTION
- O MARS -- SCIENTIFIC PROBES
- O DEEP SPACE SATELLITE -- PRIME POWER SUPPLY
- O SPACE PROCESSING/MANUFACTURING

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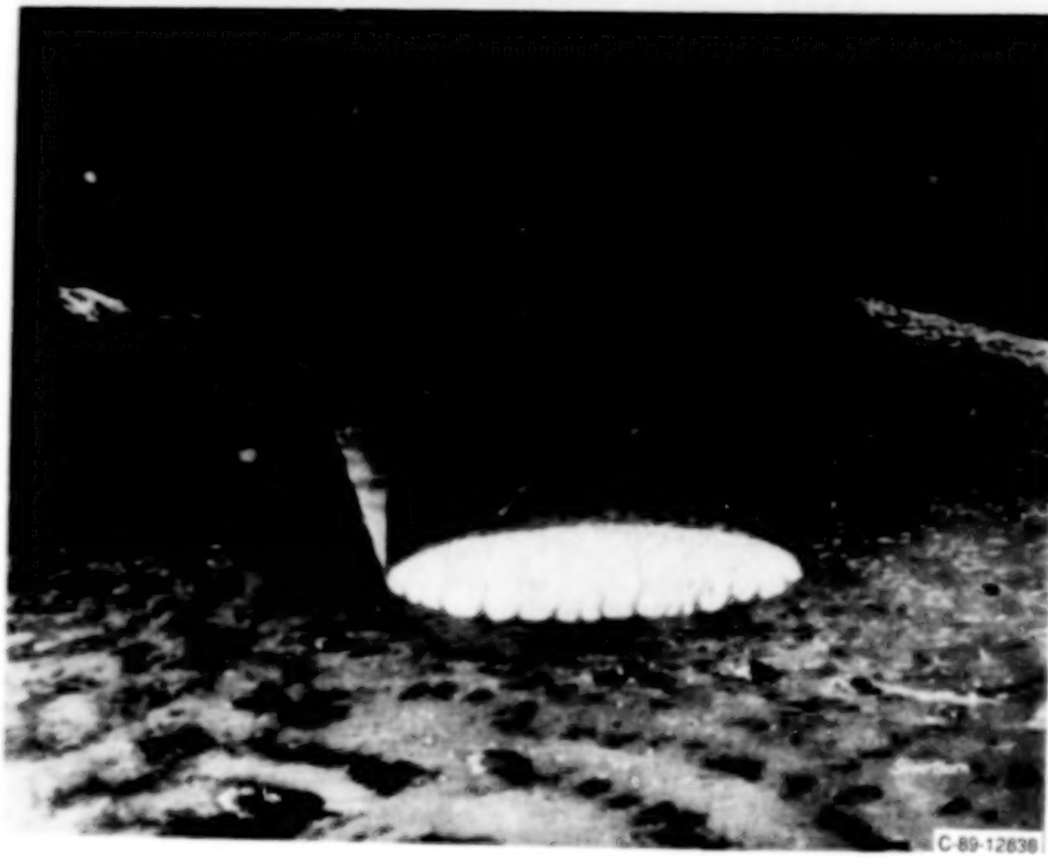

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MILESTONES

O	BEAM TRANSMISSION CHARACTERIZATION	5/88
O	TEST OF MOPA SYSTEM	12/88
O	OTHER GAS LASER ALTERNATIVES Na_2, HgBr	12/88
O	Nd^{3+} LIQUID LASER EVALUATION	6/88
O	SOLID STATE LASER EVALUATION Nd^{3+}: YAG, Nd^{3+}: GSGG, Nd^{3+}: YLF	3/88
O	PREFLIGHT EXPERIMENT GROUND TESTING	3/89
O	FLIGHT EXPERIMENT -- PLAN/DESIGN	?

SUMMARY AND CONCLUSION

- O SPACE-BORNE SOLAR-PUMPED LASER SYSTEMS ARE VIABLE OPTIONS FOR LASERS FOR FREE SPACE POWER TRANSMISSION. PRIME POWER SOURCE, SUN, IS FREE AND THE SYSTEM WITH 1.3- μm WAVELENGTH IS SUITABLE FOR TRANSMISSION OVER 1000 KM (LEO-GEO DISTANCE).

- O SOLAR-PUMPED IODINE LASER SYSTEM HAS SCALABILITY AND LIGHT WEIGHT (30 TONS/MW) SUITABLE FOR SPACE-BASED OPERATION.

- O DOIDE LASER ARRAYS DRIVEN BY SOLAR PANELS OR SOLAR DYNAMIC GENERATORS COULD BE ANOTHER CANDIDATE FOR THE SPACE-BASED LASER SYSTEM IF BEAM PROFILE CONTROL FOR THE LONG DISTANCE TRANSMISSION IS POSSIBLE.

- O IODINE LASER PROGRAM PROGRESSED STEADILY SINCE 1980 AND FLIGHT EXPERIMENT PROPOSED FOR 1990'S.

REFERENCES

1. Kare, J. T. ed.: Proceed. SDIO/DARPA Workshop on Laser Propulsion. Vol. 1, Executive Summary, CONF-860778 LLNL. Nov 1986.

2. De Young, R. J.; Walberg, G. D.; Conway, E. J.; and Jones, L. W.: A NASA High-Power Space-Based Laser Research and Applications Program. NASA SP-464, 1983.

3. Conway, E. J.; De Young, R. J.; Lee, J. H.; Williams, M. D.; and Schuster, G. L.: "Comparison of 1-MW Electrically Driven Lasers for Space Power Transmission Applications," (to be published as NASA TM, 1988).

4. Lee, J. H.; Weaver, W. R.: "A Solar Simulator-Pumped Atomic Iodine Laser," Appl. Phys. Lett.; 39, 137, (1981).

5. Lee, J. H.; Wilson, J. W.; Enderson, T.; Humes, D. H.; Weaver, W. R.; and Tabibi, M.: Opt. Commun., 53, 367, (1985).

6. Wilson, J. W.; and Lee, J. H.: "Modeling of a Solar-Pumped Laser," Virginia J. Sci., 31 34 (1980).

7. De Young, R. J.; Walker, H. G.; Williams, M. D.; Schuster, G. L.; and Conway, E. J.: Preliminary Design and Cost of a 1-Megawatt Solar-Pumped Iodine Laser Space-to-Space Transmission Station, NASA TM-4002. Sept 1987.

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HIGH POWER MILLIMETER WAVE SOURCE DEVELOPMENT PROGRAM

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U.S. Department of Energy
Washington, DC 20545

HIGH POWER MILLIMETER WAVE SOURCES FOR FUSION PROGRAM

MOTIVATION:

A) FUSION APPLICATIONS
   1. BULK HEATING
   2. CONTROL OF MHD MODES
   3. RADIAL TEMPERATURE PROFILE CONTROL
   4. PRE-IONIZATION AND START-UP
   5. CURRENT DRIVE
   6. DIAGNOSTICS

B) ISOTOPE SEPARATION

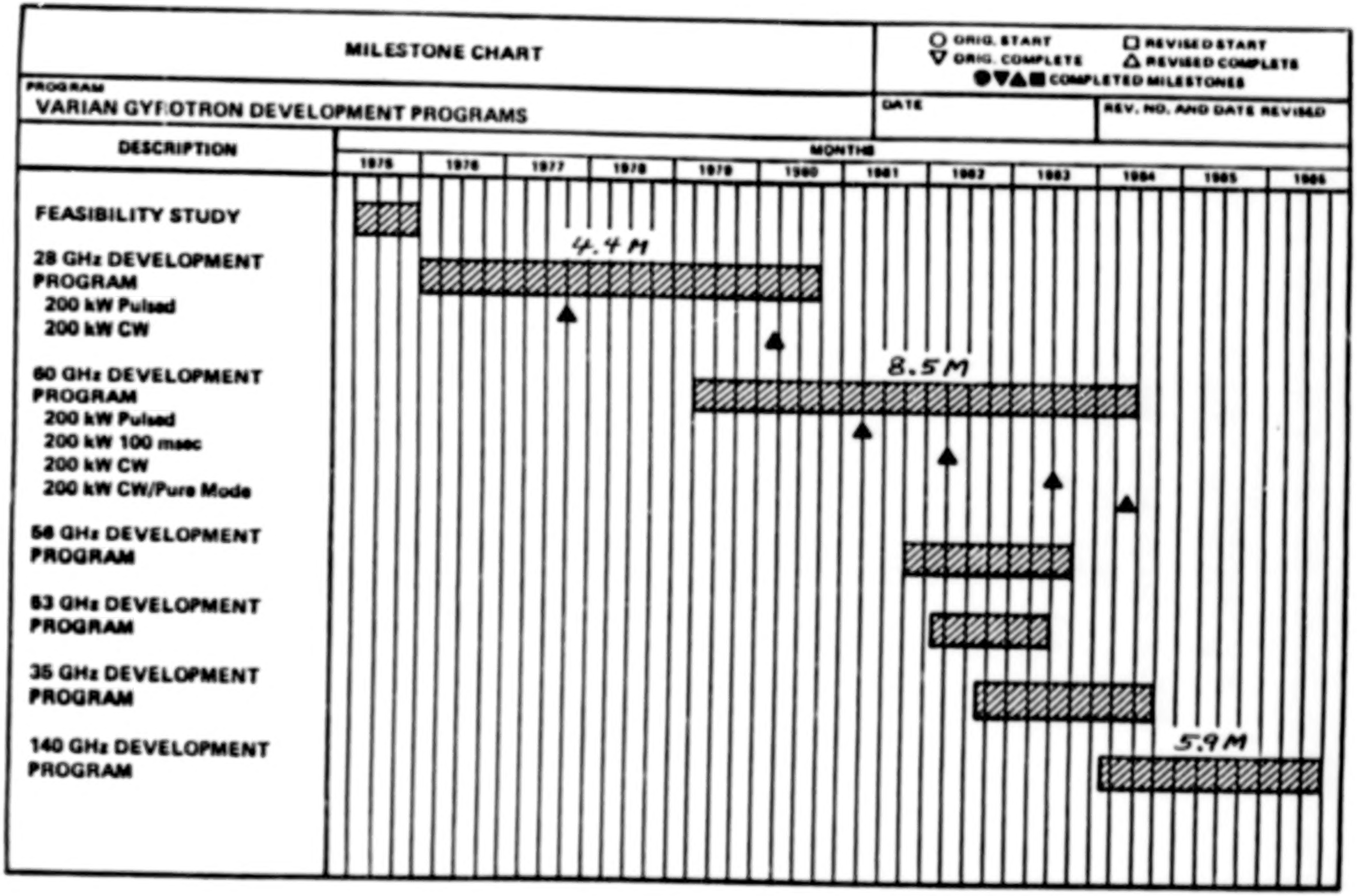
C) POWER TRANSMISSION

D) MILITARY APPLICATIONS

HIGH POWER MILLIMETER WAVE SOURCES FOR FUSION PROGRAM

HISTORY OF INDUSTRIAL DEVELOPMENT OF GYROTRONS:

- INITIATED 28 GHZ, 200 KW, CW GYROTRON DEVELOPMENT IN 1976
  SUCCESSFULLY COMPLETED IN 1980
- INITIATED 60 GHZ, 200 KW, CW GYROTRON DEVELOPMENT IN 1980
  SUCCESSFULLY COMPLETED IN 1984
- INITIATED 140 GHZ, 100 KW, CW GYROTRON DEVELOPMENT IN 1984
  SUCCESSFULLY COMPLETED IN 1986
- INITIATED 140 GHZ, 1 MW, PULSED/CW GYROTRON DEVELOPMENT IN 1986
  PROGRESSING SATISFACTORILY


MILESTONE CHART
ORIG. START
ORIG. COMPLETE
REVISED START
REVISED COMPLETE
COMPLETED MILESTONES
PROGRAM
VARIAN GYROTRON DEVELOPMENT PROGRAMS
DATE
REV. NO. AND DATE REVISED
DESCRIPTION
MONTHS
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
FEASIBILITY STUDY
28 GHz DEVELOPMENT PROGRAM
200 kW Pulsed
200 kW CW
4.4M
60 GHz DEVELOPMENT PROGRAM
200 kW Pulsed
200 kW 100 msec
200 kW CW
200 kW CW/Pure Mode
8.5M
56 GHz DEVELOPMENT PROGRAM
53 GHz DEVELOPMENT PROGRAM
35 GHz DEVELOPMENT PROGRAM
140 GHz DEVELOPMENT PROGRAM
5.9M

HIGH POWER MILLIMETER WAVE SOURCES
FOR FUSION PROGRAM

MAIN TECHNICAL OBJECTIVE: PLASMA HEATING

REQUIREMENTS:

CURRENT: 200 KW - 2 MW @ 60 GHZ, CW

NEAR-TERM: 6 MW @ 115 GHZ, CW

MID 90'S: 10-30 MW @ 280 GHZ, CW

ECH SOURCE DEVELOPMENT PROGRAM STRATEGY

DEVELOP 140 GHZ, 1 MW, PULSED GYROTRON IN A COST-EFFECTIVE WAY USING

- VARIAN'S PAST EXPERIENCE
- ONGOING WHISPERING GALLERY EXPERIMENTS AT MIT

IN PARALLEL

- ESTABLISH DATA BASE FOR 280 GHZ, WHISPERING GALLERY MODE AT MIT
- ENGINEERING FEASIBILITY TESTS AND CONCEPTUAL DESIGNS AT VARIAN
- EVALUATE NEW CONCEPTS WHICH COULD BETTER MEET THE FUSION NEEDS
  - SMALL PERIODIC FEM
  - CARM
  - QUASI-OPTICAL GYROTRON
  - SDIO SUPPORTED PULSED FEL
  - TRW'S CW FEL
  - SCIENCE RESEARCH LAB'S PULSED FEL
  - RUSSIAN 2.1 MW COAXIAL CAVITY GYROTRON

OFFICE OF FUSION ENERGY CURRENT DEVELOPMENT ACTIVITIES

TASK	INSTITUTION	P.I.	1987	BUDGET 1988	1989
140 GHZ GYR.	VARIAN	JORY/FELCH	1000	1500	2000
140/280 GHZ	MIT	TEMKIN	400	450	?
Q-O GYR.	NRL	MANHEIMER	205	250	?
SMALL PER. FEL	U. MD	GRANATSTEIN	250	250	?
TRANSM. SYSTEM	U. WISC.	VERNON	100	100	?
LLNL/FEL-DRIVER	LLNL	CAPLAN	0	1100	?
MISC. ---->					
TOTAL (APPROXIMATELY)			2000	3900	4100

1 MW, 140 GHz GYROTRON EXPERIMENT DESIGN PHILOSOPHY

- DEMONSTRATE 1 MW AT 140 GHz FOR SHORT PULSES WITHIN A SHORT TIME PERIOD WITH PROVIDED FUNDS

  (NOT A TRUE DEVELOPMENT EFFORT WITH MULTIPLE EXPERIMENTS AND PARALLEL DESIGN APPROACHES)

- DEMONSTRATE SEVERAL HUNDRED kW CW TO BEGIN BUILDING TECHNOLOGY BASE FOR 1 MW CW

- BUILD UPON
  - CURRENT 140 GHz DEVELOPMENT WORK
  - 1 MW STUDY OF 1983
  - 1 MW EFFORT AT MIT
  - VARIAN IR & D OVER PAST 1-1/2 YEARS

OSCILLATOR TECHNOLOGY CONCERNS

- WINDOWS
- MODE COMPETITION IN LARGER CAVITIES
- CAVITY WALL COOLING
- OUTPUT COUPLING
- BEAM TUNNEL LOADING

ECH SOURCE DEVELOPMENT PROGRAM PLAN

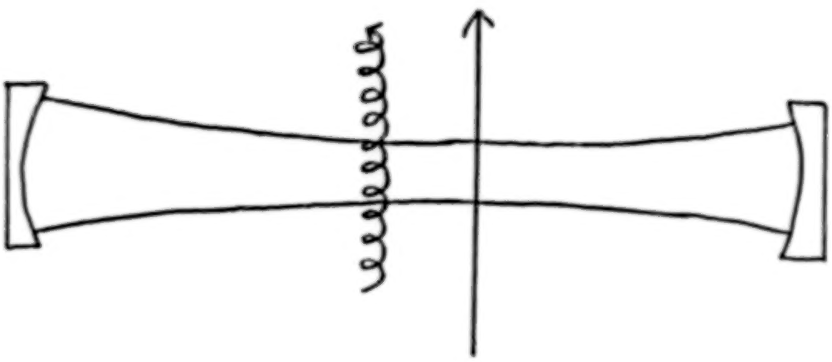
(BASED ON CURRENT FUNDING)

- CONTINUE WITH THE 140 GHZ, 1 MW, GYROTRON DEVELOPMENT AT VARIAN
- INITIATE 280 GHZ WHISPERING GALLERY STUDIES AT MIT
- ESTABLISH A CW, MEGAWATT TEST FACILITY BY 1990
- CONDUCT SINGLE PULSE FEL HEATING EXPERIMENT ON MTX
- REEVALUATE DATA BASE AND INITIATE 280 GHZ, MEGAWATT INDUSTRIAL SOURCE DEVELOPMENT IN FY 1990

QUASI-OPTICAL GYROTRON DEVELOPMENT

Wallace Mannheimer
Naval Research Laboratories
Washington, DC 20375

Quasi-Optical Gyrotron (NRL)



Advantages:

Much less of a problem with wall loading

Beam collection and radiation extraction at different places;

Especially important if depressed collection is used

Difficulties

Complicated magnet design

DOE Requirement:

Tube for ECRH of CIT and subsequent reactors

$P > 1$ MW

$f = 300$ GHz (Or maybe as high as 600 GHz)

$\eta \geq 20\%$

CW (Or at least 3 second) relevant

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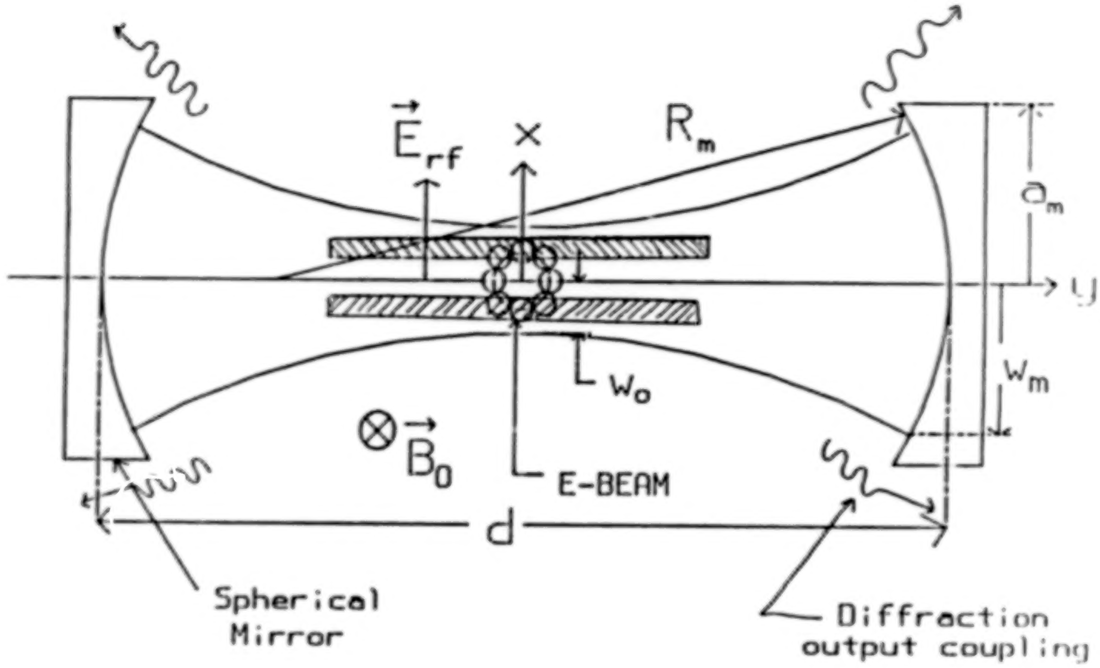
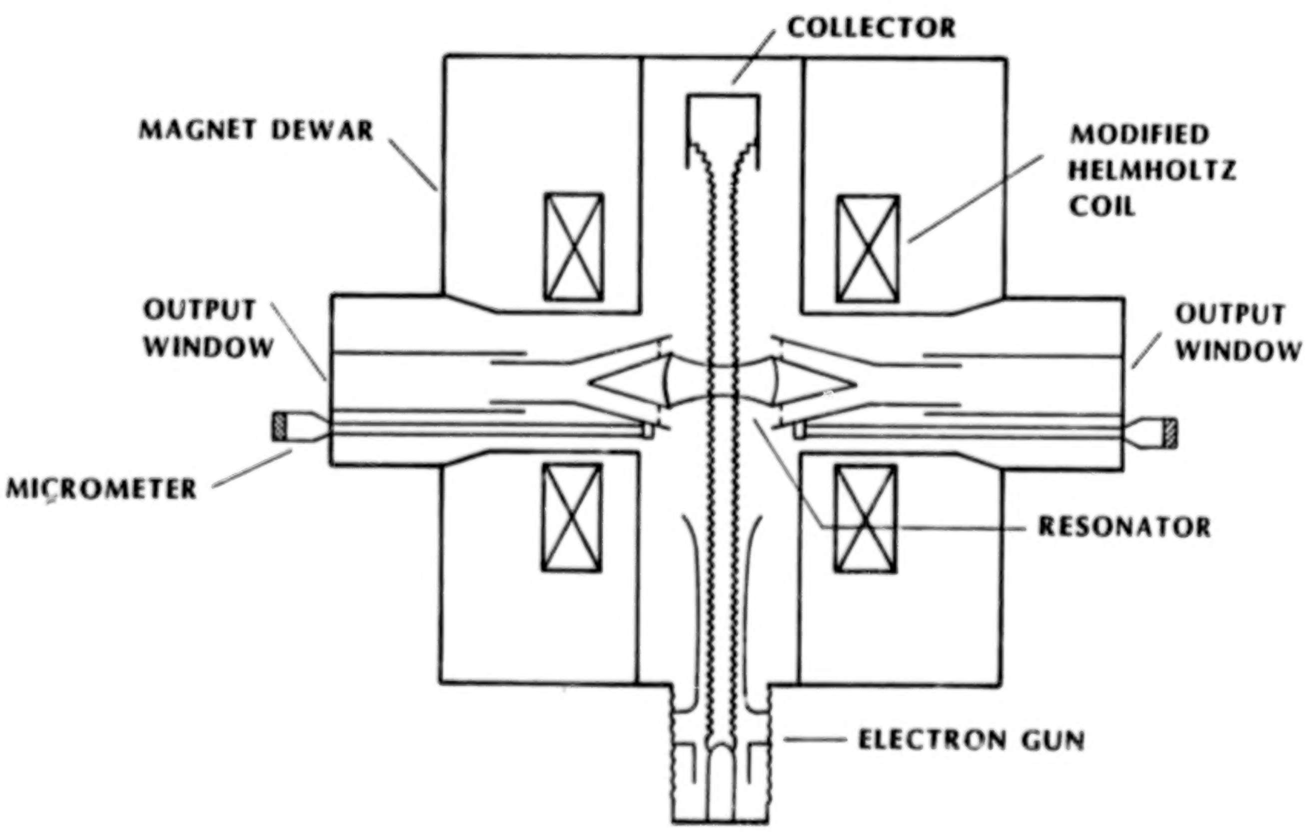
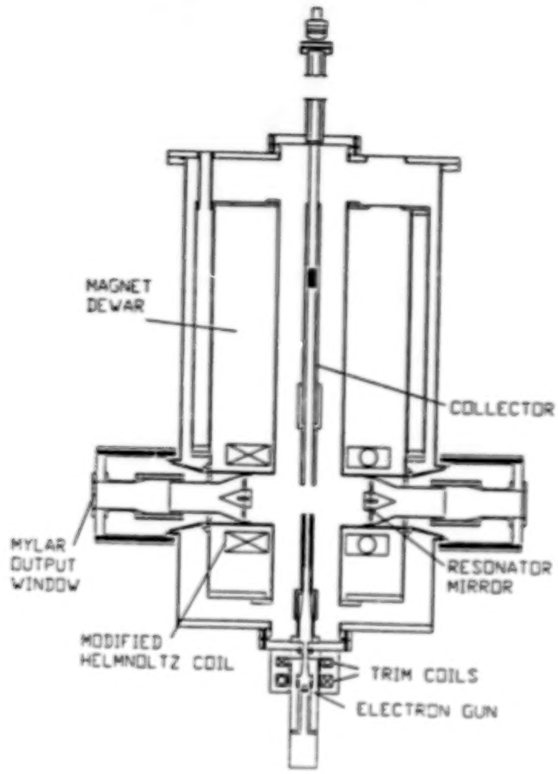
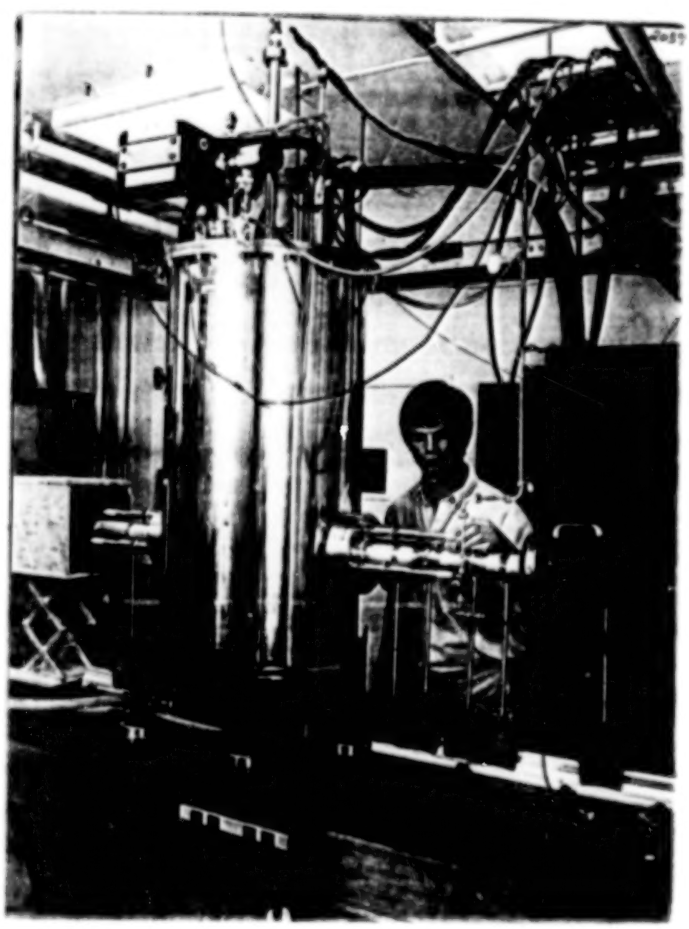
QUASI-OPTICAL RESONATOR CONFIGURATION





NRL QUASI-OPTICAL GYROTRON





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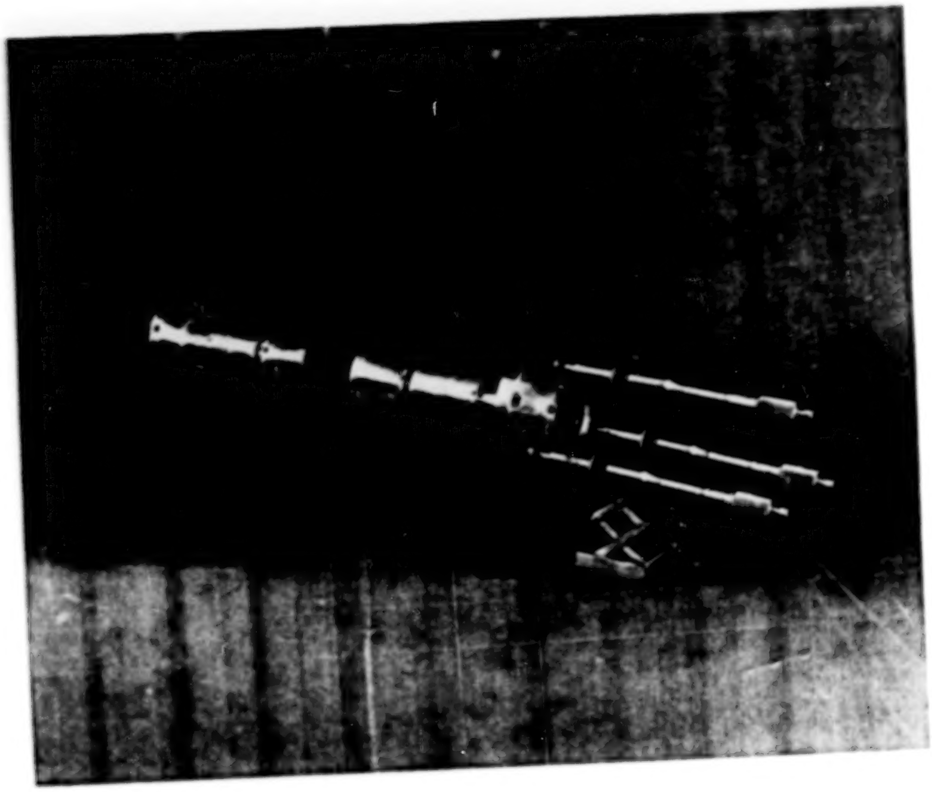

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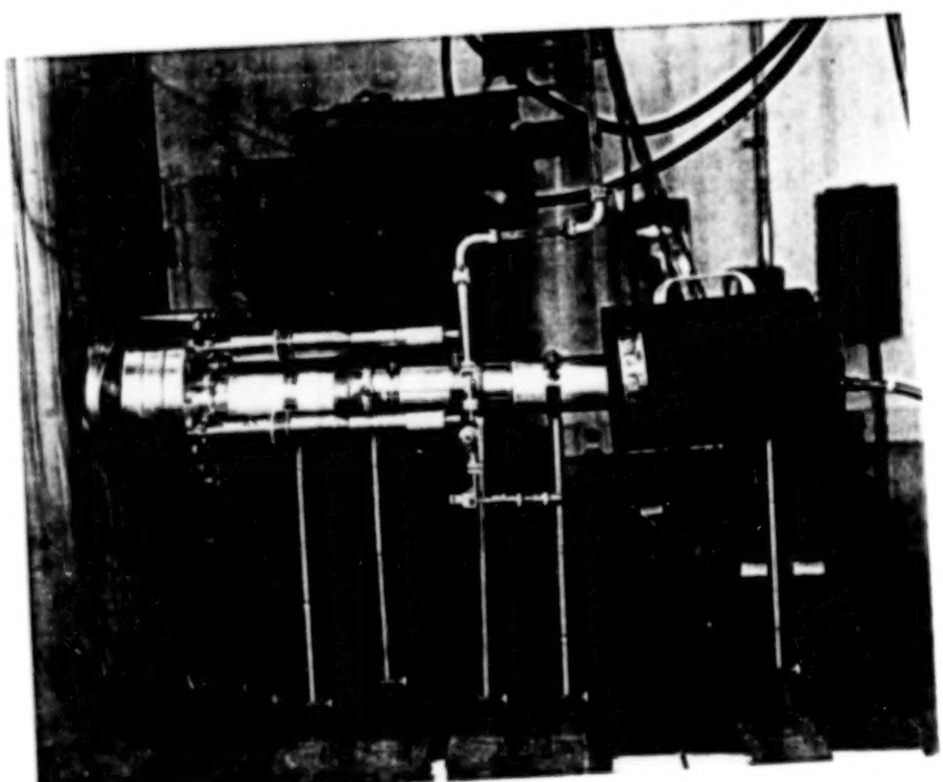

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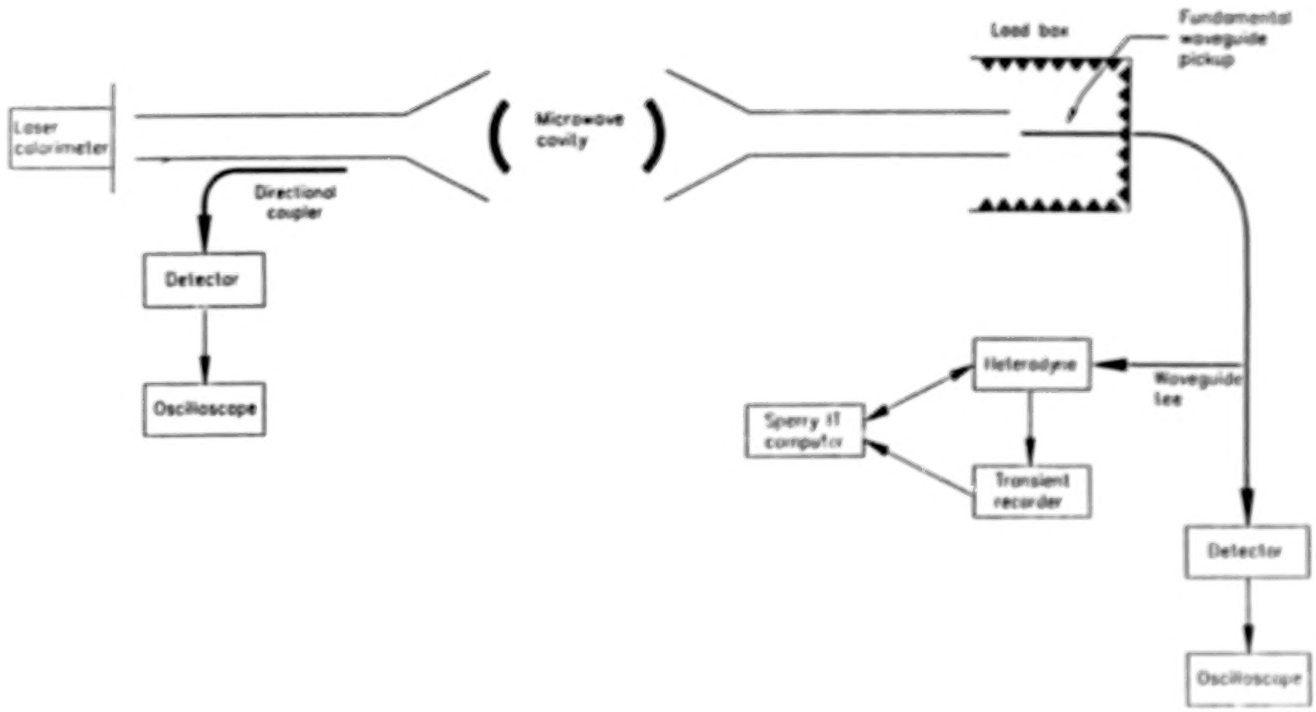
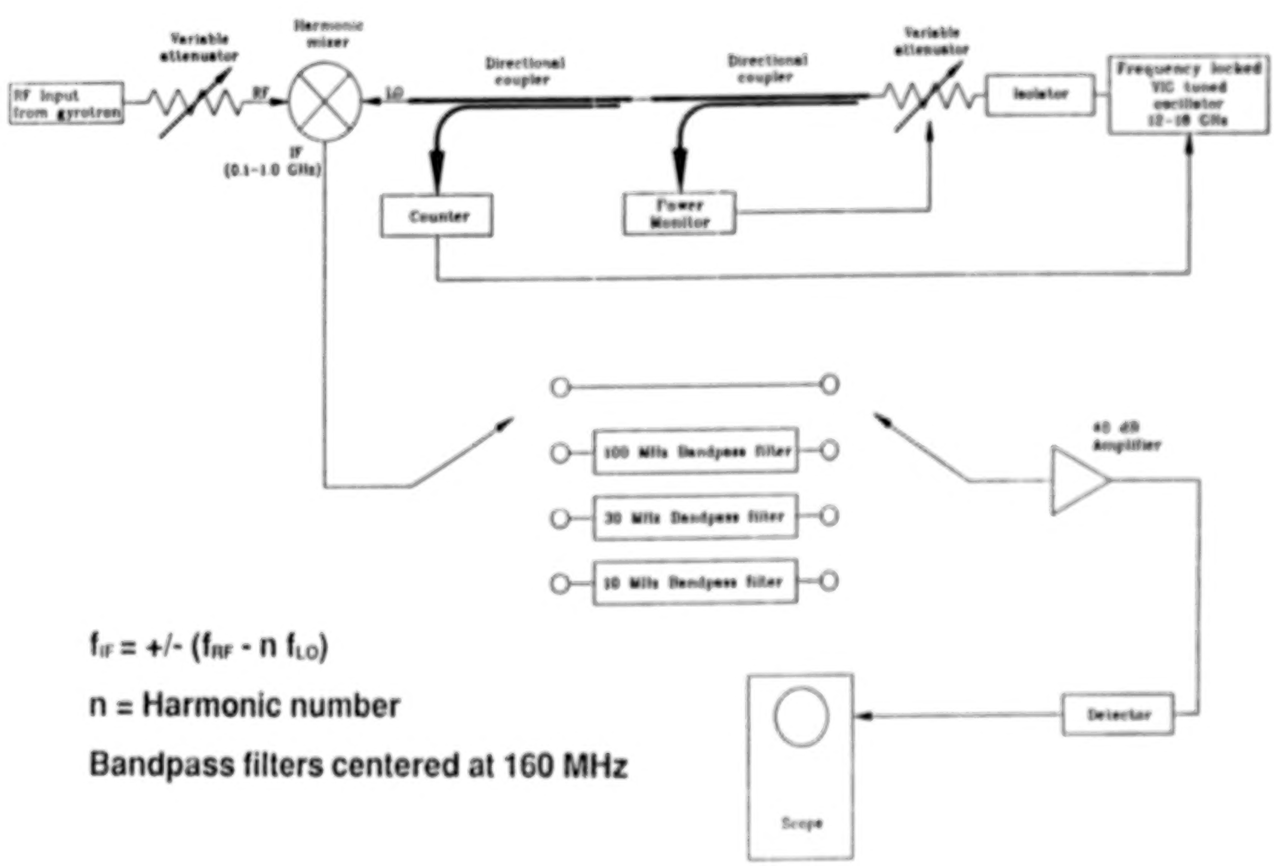
Diagnostic Setup



Heterodyne Diagnostic

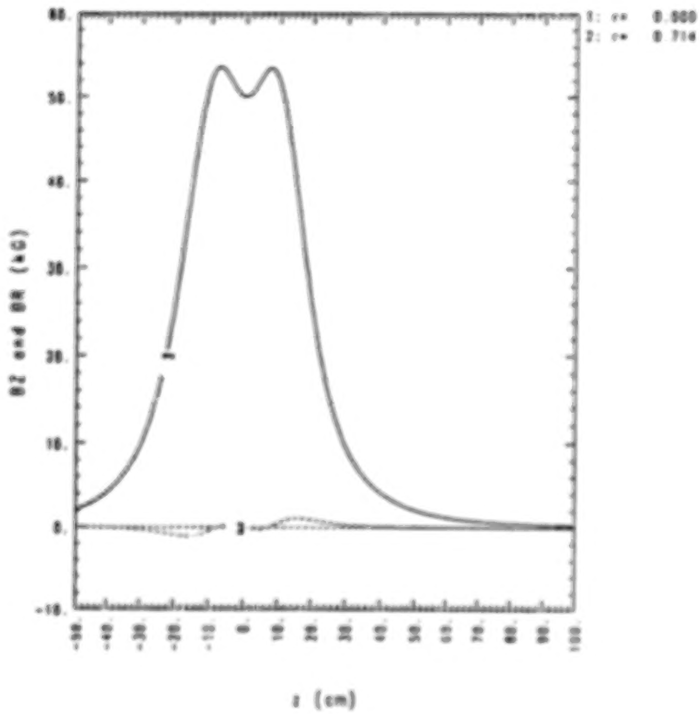


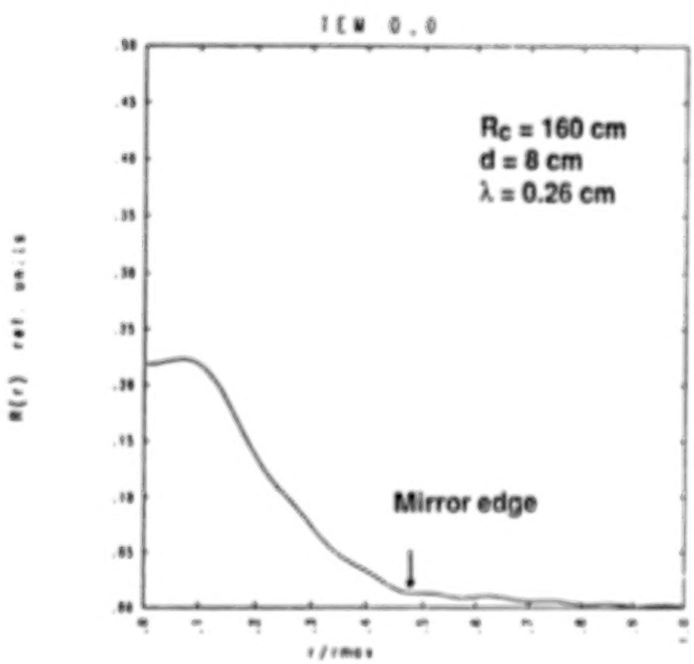
$f_{IF} = +/- (f_{RF} - n\, f_{LO})$

n = Harmonic number

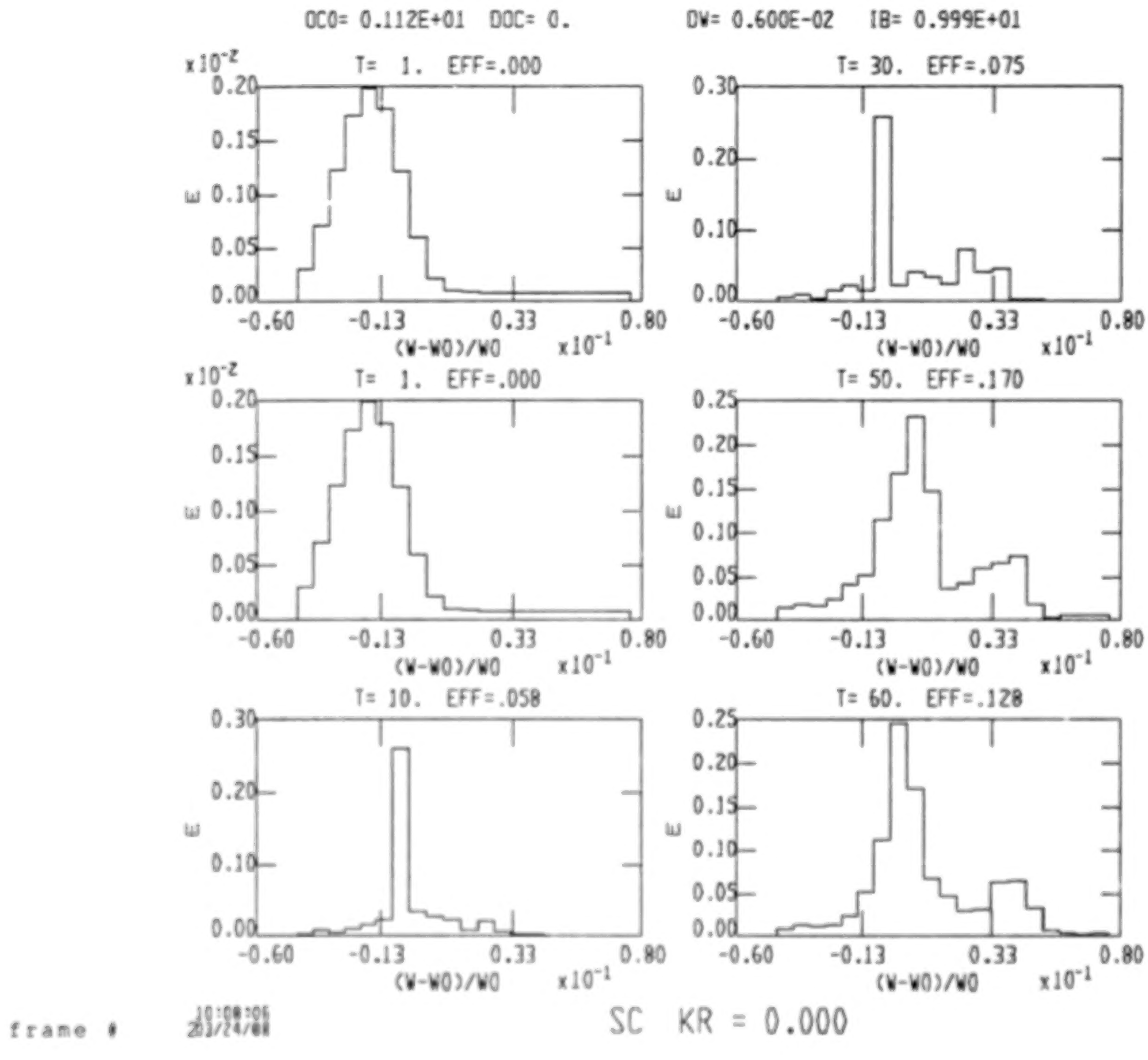
Bandpass filters centered at 160 MHz

Magnetic Field Profile



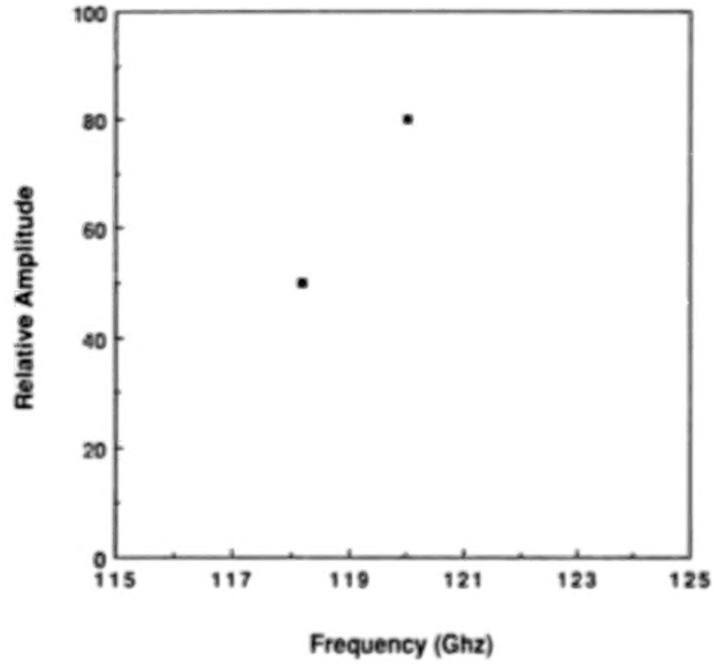


Loss	Q	% Transmitted	% of Total
Diffraction	5.082e+04	3.415e-01	8.22
Slot(s)	5.060e+03	3.814e+00	91.78
Total	4.653e+03	4.155e+00	

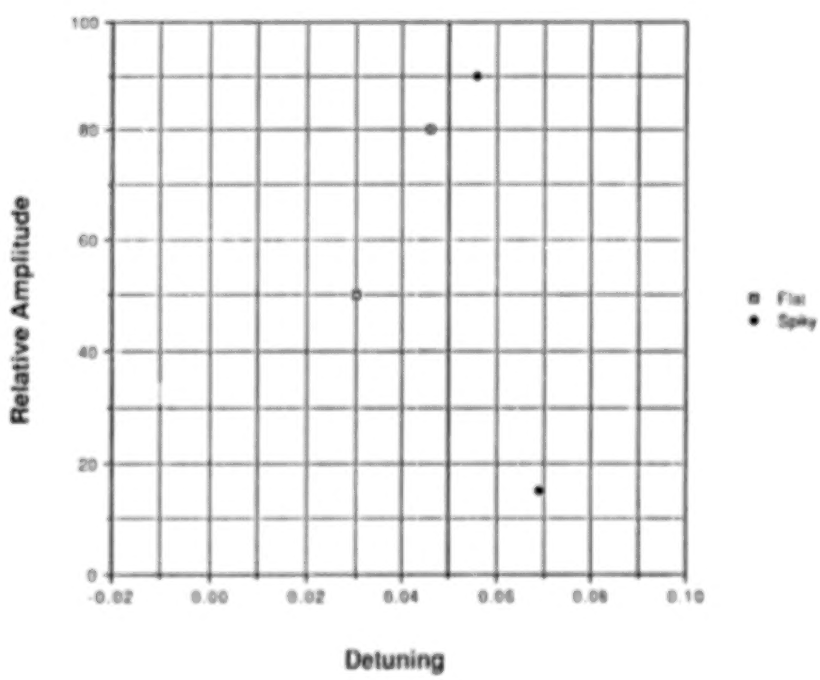


OCO= 0.112E+01 DOC= 0.
DW= 0.600E-02 IB= 0.999E+01
T= 1. EFF=.000
T= 30. EFF=.075
T= 1. EFF=.000
T= 50. EFF=.170
T= 10. EFF=.058
T= 60. EFF=.128
E
(W-W0)/W0
x10^-1
x10^-2
frame #
SC KR = 0.000

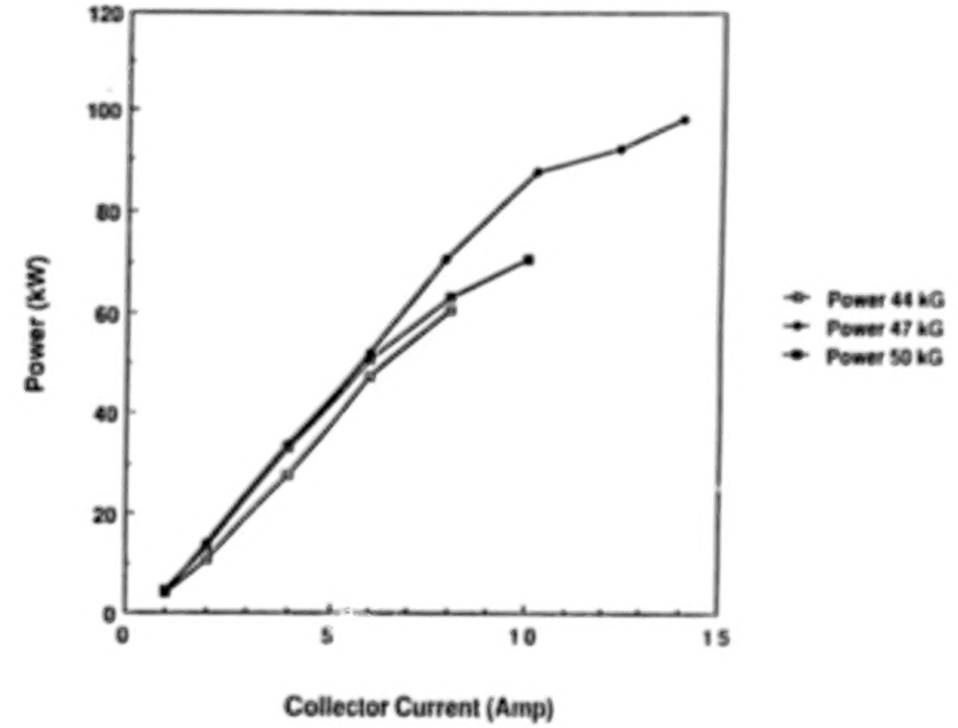
Mode Spectrum for QOG at 75 kV, 14 Amp and 47 kG



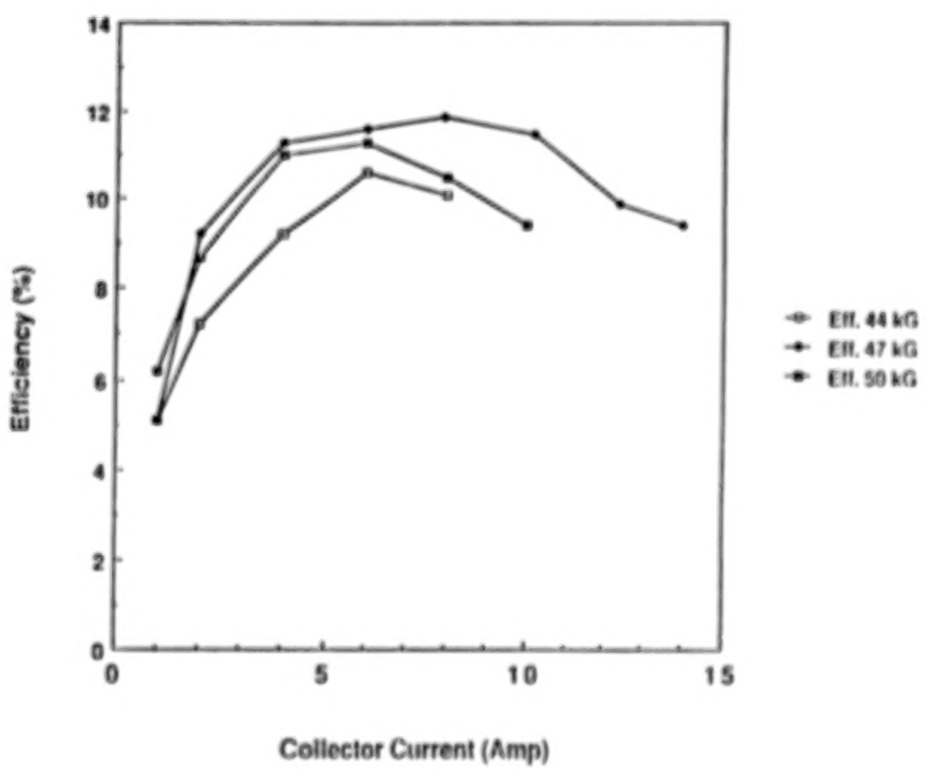
Mode Spectrum for 75 kV, 14 Amp and 47 kG

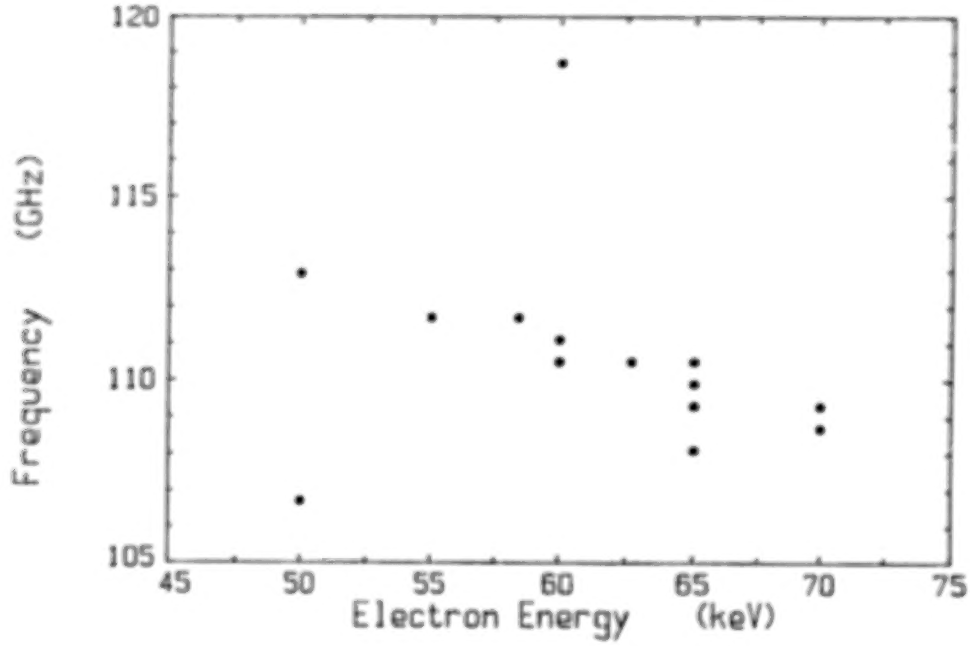


Operation at 75 kV and 20 cm Separation

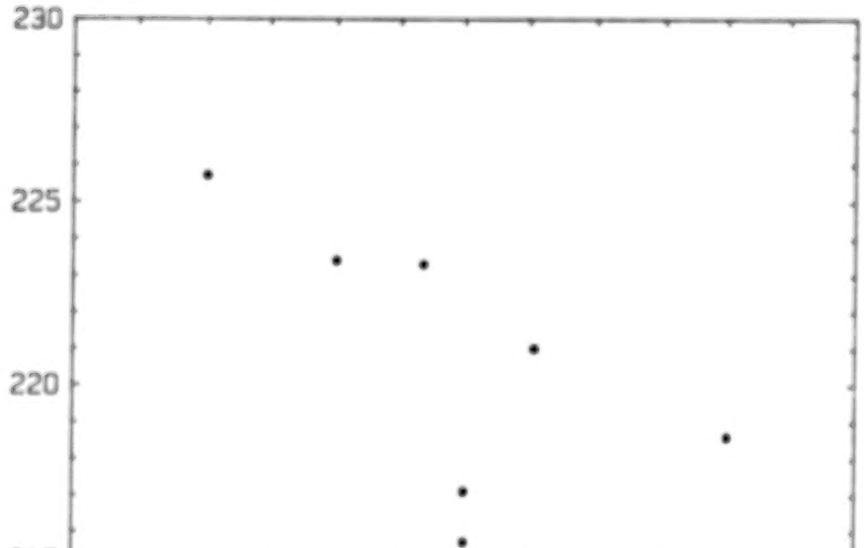


Operation at 75 kV and 20 cm Separation





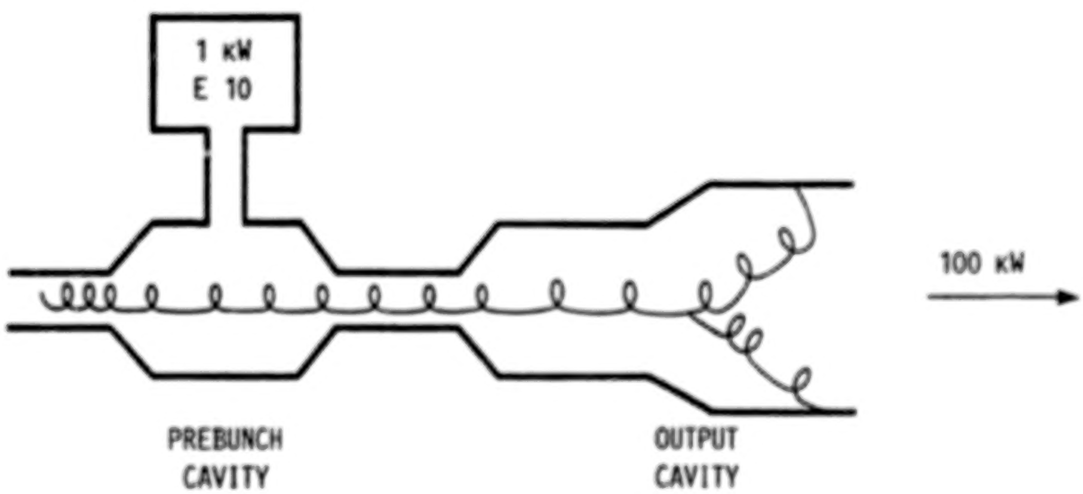
25 cm Mirror Separation



FUTURE PLANS

- INSTALL 80 keV, 35A VUW8144 (MIT) ELECTRON GUN
- MODE CONTROL BY MODE LOCKING AND BY STRUCTURED MIRRORS
- HARMONIC OPERATION
- ACHIEVE P = 1 MW WITH USE OF A 6 MW SHEET BEAM ELECTRON GUN

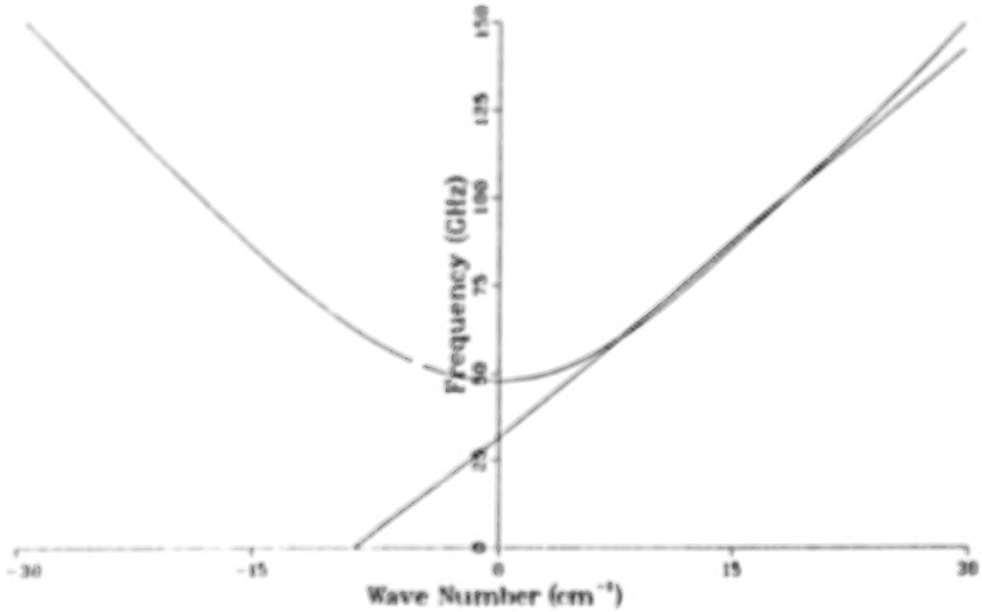
PHASE LOCKED 85 GHz GYROTRON

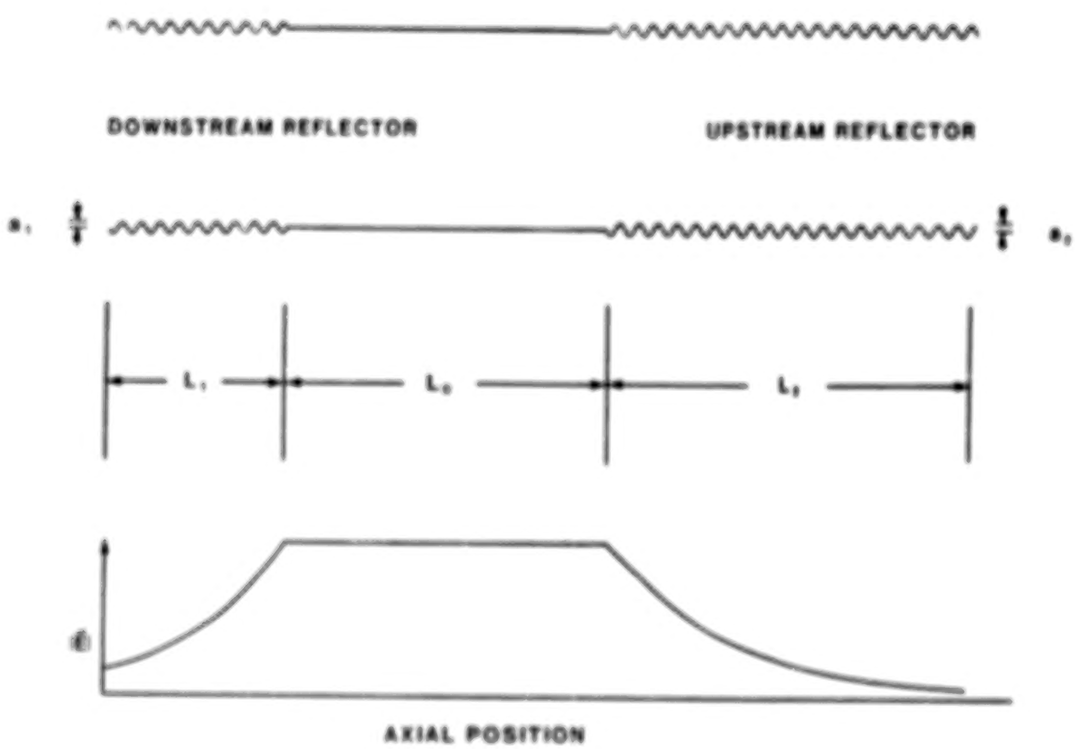


ISSUES

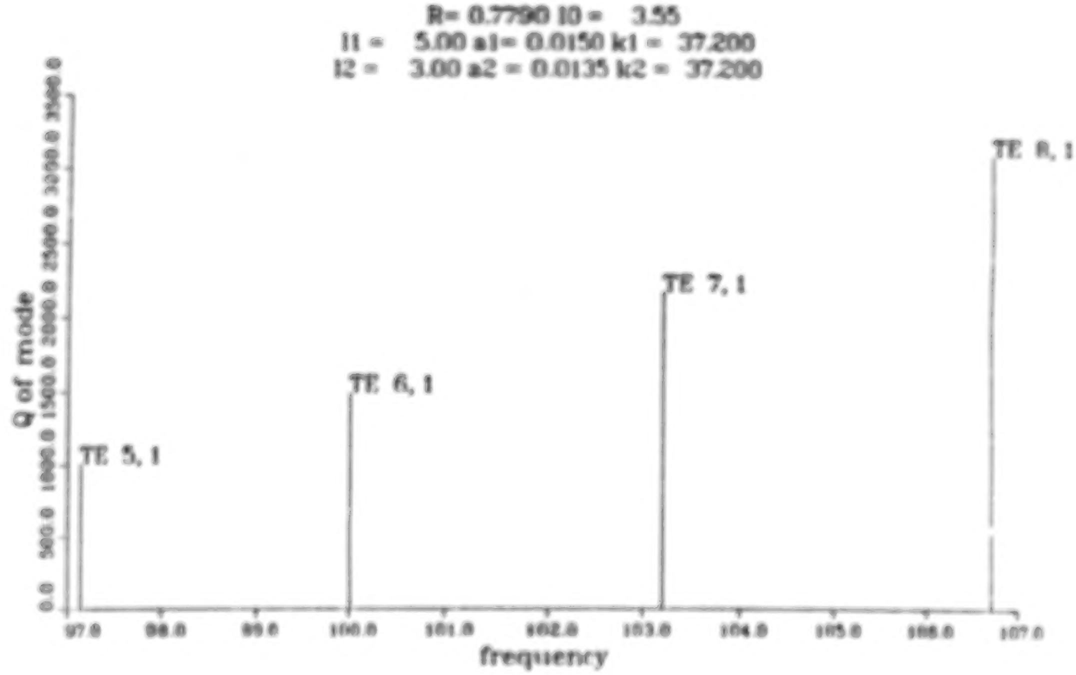
- STABILIZE PREBUNCHING CAVITY
- ISOLATE CAVITIES
- MAXIMIZE LOCKING BANDWIDTH

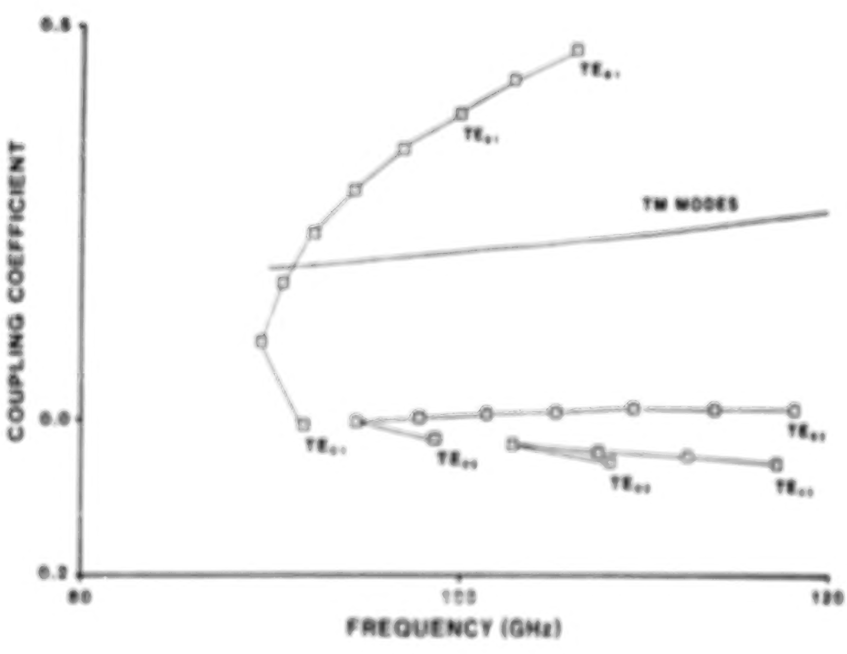
CARM Dispersion Relation

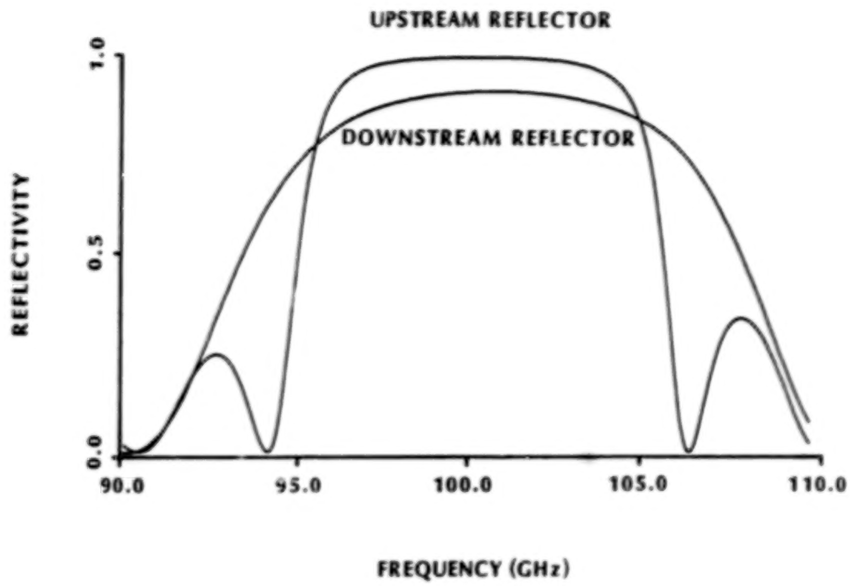




Bragg Cavity Modes







PRELIMINARY DESIGN PARAMETERS OF 250 GHz LONG PULSE CARM EXPERIMENT

<u>Electron Beam</u>

Gun type	temperature-limited MIG
Beam cross section	annular
Beam diameter	1.1 cm
Beam voltage	500 kV
Beam current	100 amp max
Pulse width	1 μsec
Velocity pitch ratio	0.71
Pitch angle spread limit	2 percent
Energy spread limit	7 percent

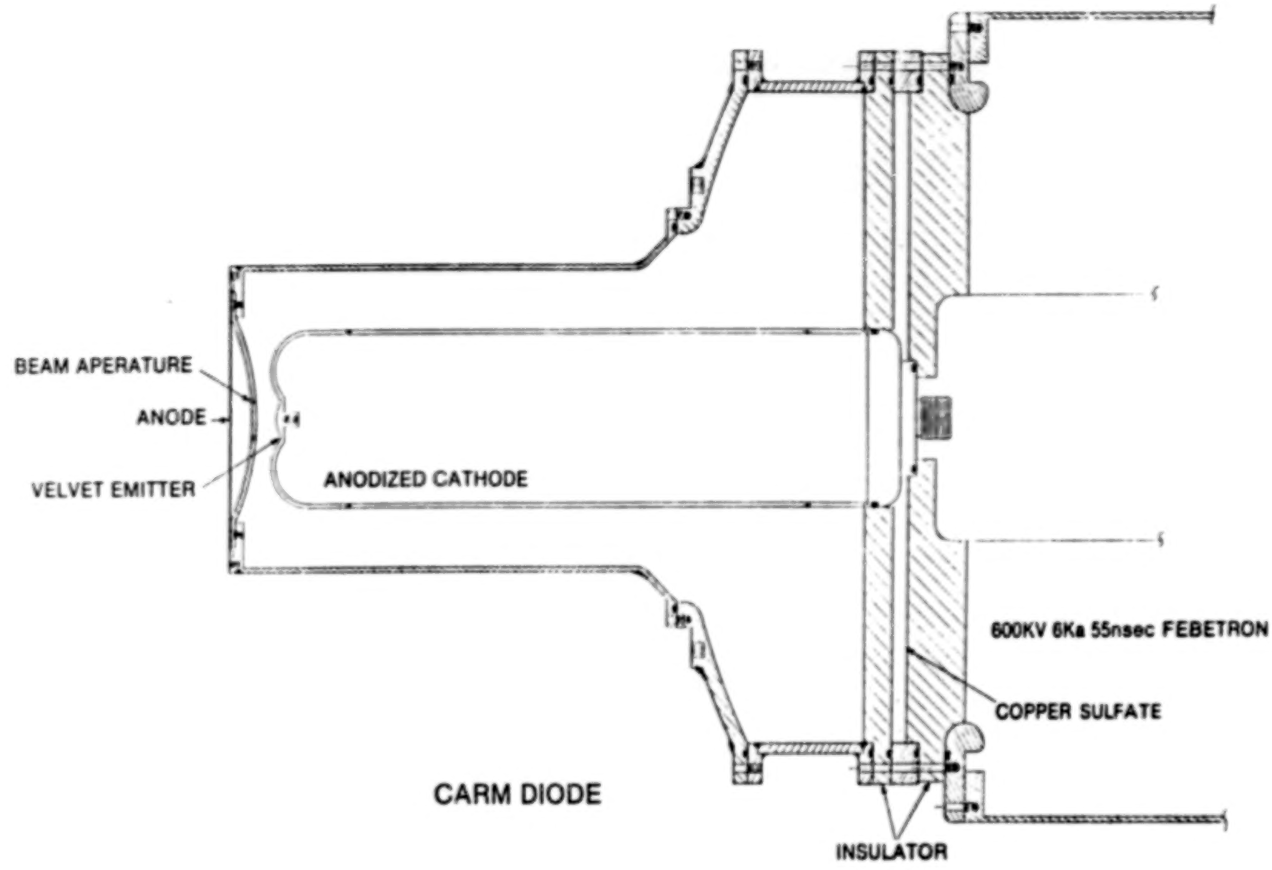
<u>Resonator</u>

Cavity type	circular wave guide
Reflector type	Bragg reflector
Output reflectivity	92 percent
Operating mode	TE_{14} (volume mode)
Wave group velocity	0.97c
Cavity length	~ 10 cm
Cavity diameter	1.8 cm
Ohmic heating	3 kW/cm^2

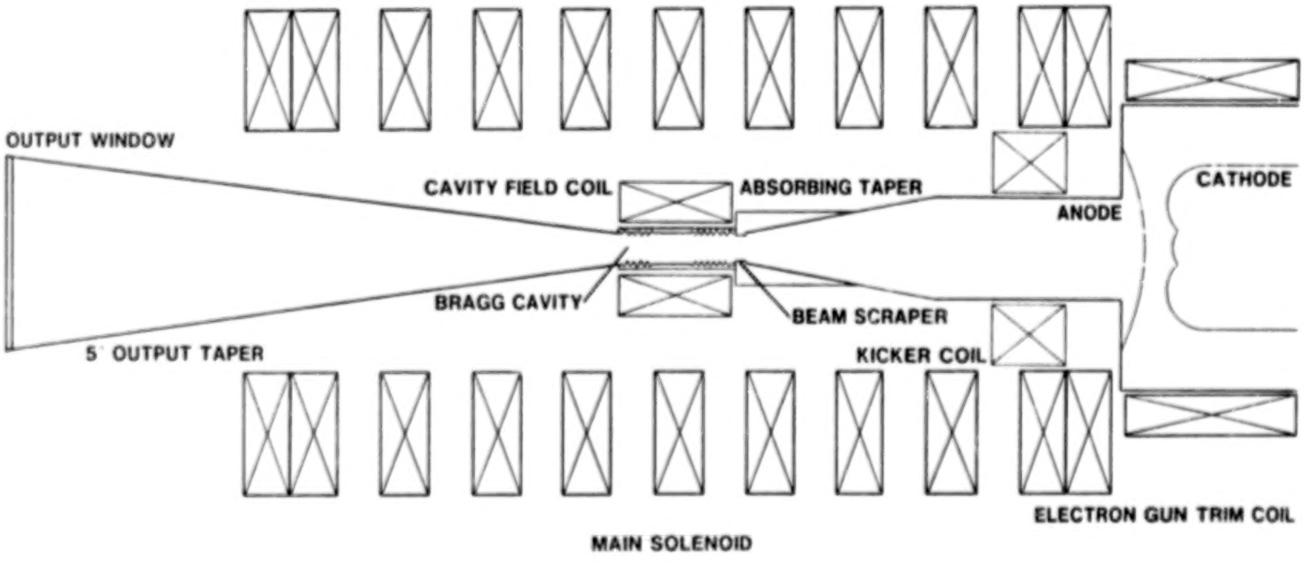
<u>Magnet</u>

Magnet type	superconducting
Cavity magnetic field	~ 55 kG

Predicted efficiency	20 to 40 percent
Predicted output power	10 MW


BEAM APERATURE
ANODE
VELVET EMITTER
ANODIZED CATHODE
600KV 6Ka 55nsec FEBETRON
COPPER SULFATE
INSULATOR

CARM DIODE


OUTPUT WINDOW
CAVITY FIELD COIL
ABSORBING TAPER
CATHODE
ANODE
BRAGG CAVITY
BEAM SCRAPER
5' OUTPUT TAPER
KICKER COIL
ELECTRON GUN TRIM COIL
MAIN SOLENOID

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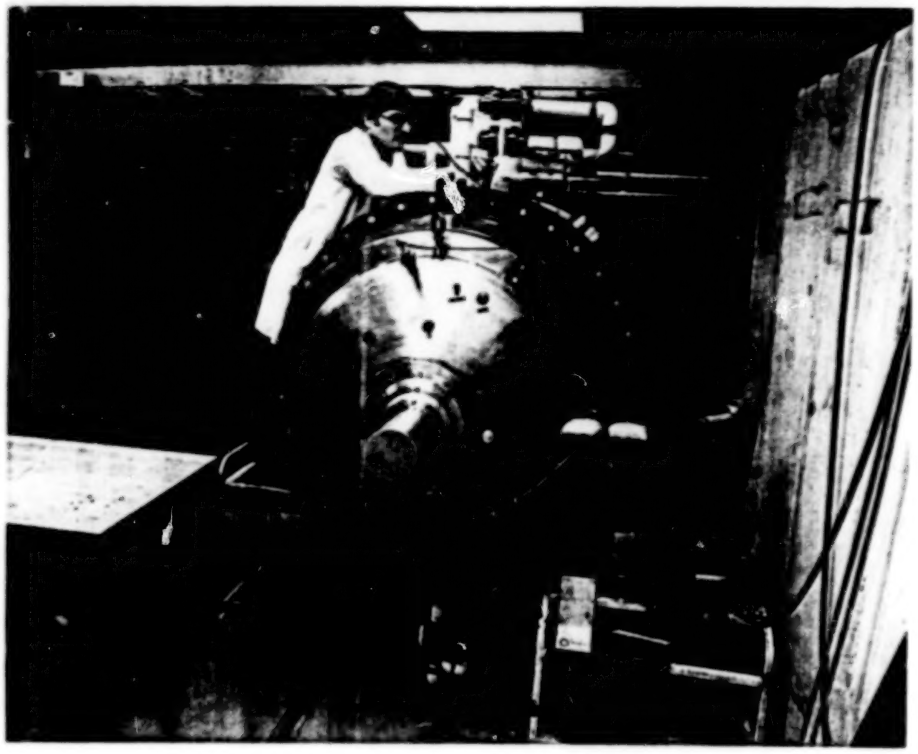

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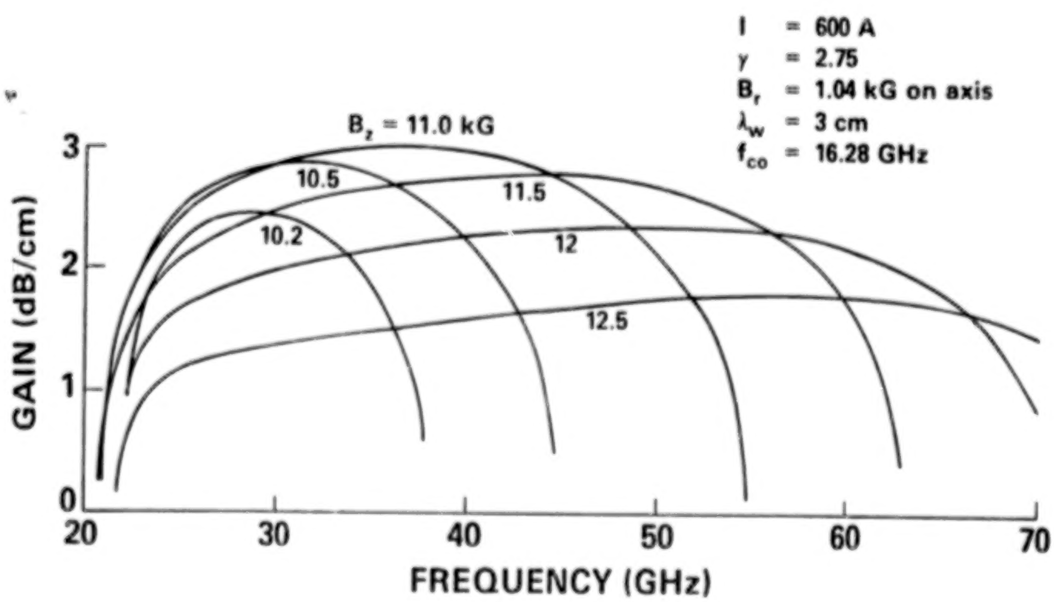
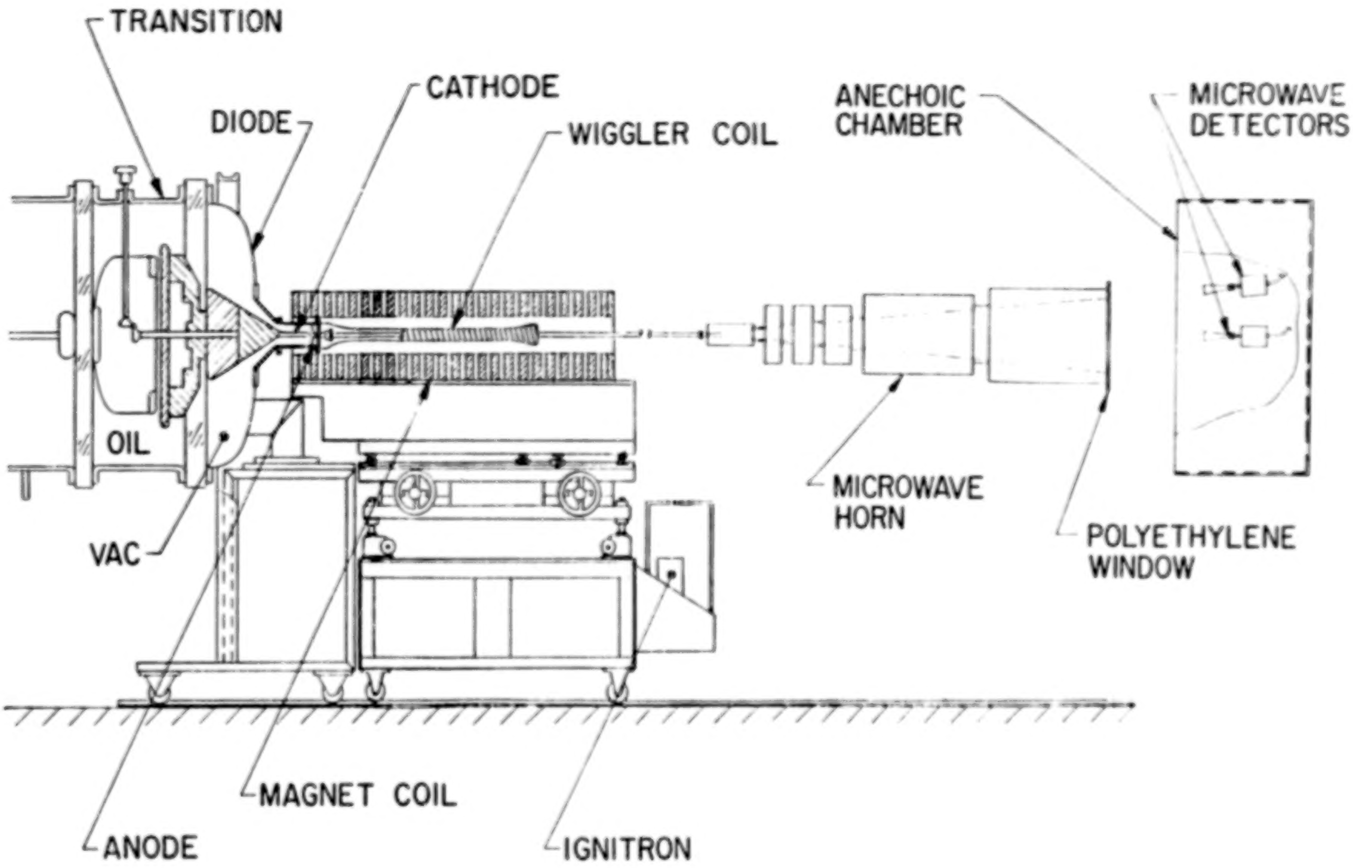
35-GHz FEL AMPLIFIER
THEORETICAL GROWTH CURVES

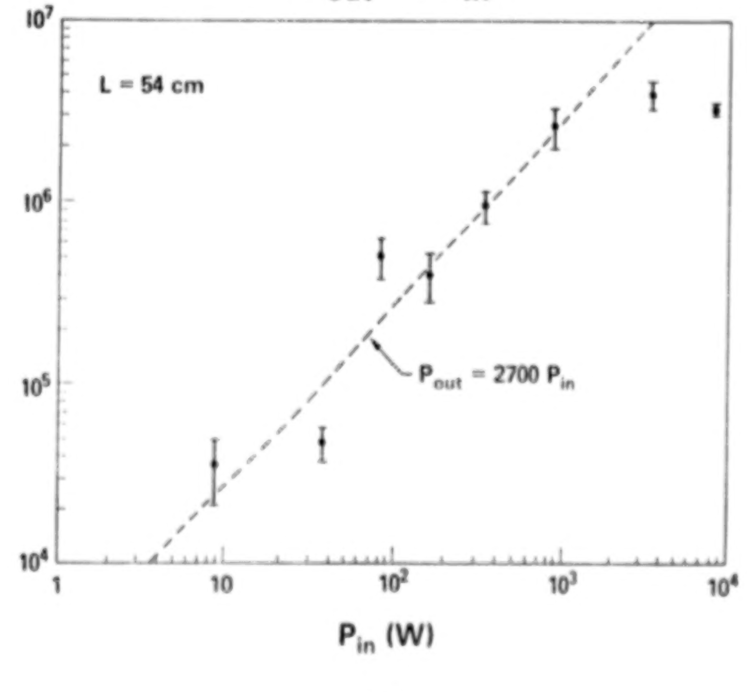




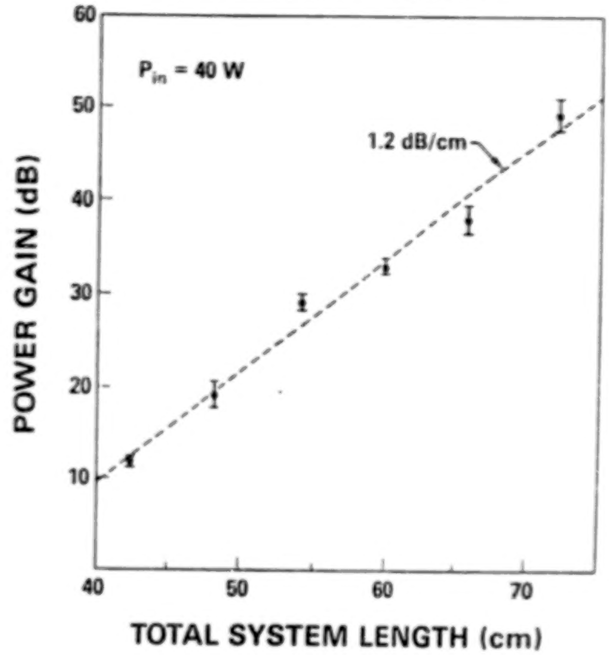
N.R.L. F.E.L. EXPERIMENT

35 GHz FEL AMPLIFIER

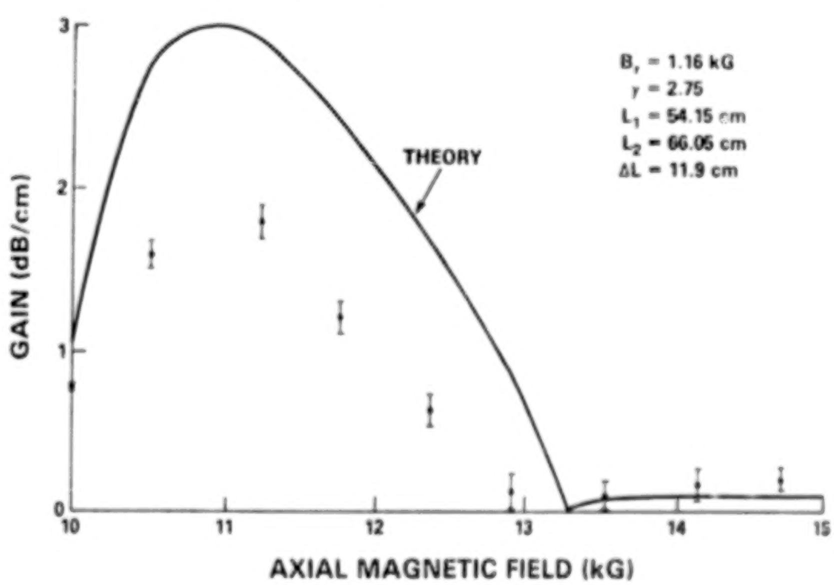
P_{out} vs P_{in}



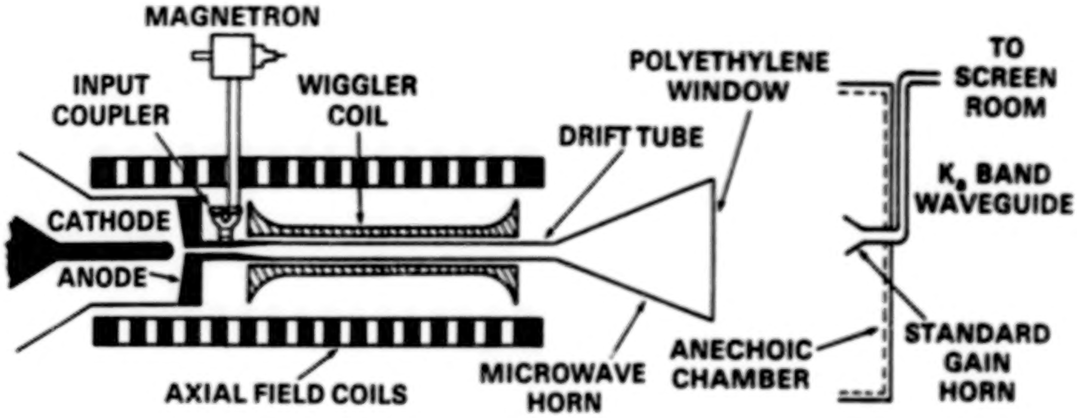
35 GHz FEL AMPLIFIER
GAIN vs LENGTH



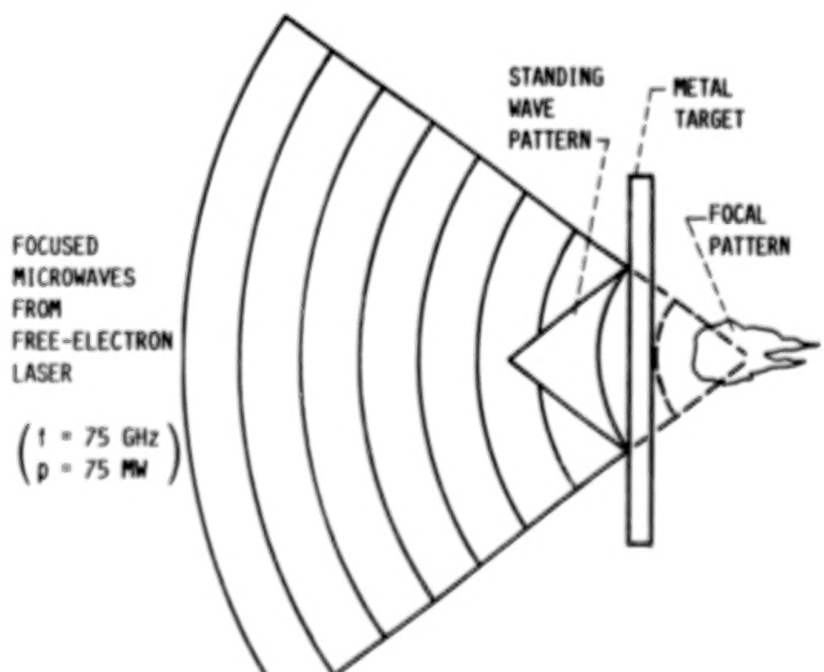
35 GHz FEL AMPLIFIER
GROWTH RATE vs AXIAL FIELD



VEBA MILLIMETER-WAVE FEL
AMPLIFIER CONFIGURATION



MICROWAVE-PRODUCED ATMOSPHERIC PRESSURE
AIR BREAKDOWN



RECTIFYING DEVICES FOR ENERGY CONVERSION: TUNGSTEN SILICIDE SCHOTTKY BARRIER DIODES AT 10.6 MICRONS*

Howard E. Jackson and Joseph T. Boyd
University of Cincinnati
Cincinnati, Ohio 45204

AN OUTLINE

MOTIVATION

BRIEFLY REVIEW THE PHYSICAL PROCESS

COMMENTS ON DESIGN

CHARACTERIZATION - INCLUDING

- A BRIEF ASIDE ON WSi_2 CHARACTERIZATION
- DEVICE RESPONSE IN THE FAR-INFRARED

CURRENT STATUS

RECOMMENDATIONS FOR FUTURE EFFORTS

OBJECTIVE

MAXIMUM IRRADIATION FROM THE EARTH IS IN THE 8 - 14 MICRON RANGE.

THIS CORRESPONDS TO A PHOTON ENERGY RANGE FROM .155 eV TO .0866 eV.

USE:

POWERING SATELLITES.

ADVANTAGE:

NO TRACKING MECHANISM REQUIRED.

ABLE TO GENERATE POWER AT ALL TIMES AND POSITIONS OF ORBIT.

*Work supported by NASA Lewis Research Center grant NAG3-583.

ENERGY BANDGAPS OF SEMICONDUCTORS

Silicon (Si)	1.12 eV
Germanium (Ge)	0.7 eV
Gallium Arsenide (GaAs)	1.4 eV
Gallium Phosphide (GaP)	2.3 eV
Indium Arsenide (InAs)	0.4 eV
Indium Phosphide (InP)	1.3 eV
Indium Antimonide (InSb)	0.2 eV
Cadmium Sulphide (CdS)	2.6 eV
Lead Sulphide (PbS)	0.4 eV
Lead Selenide (PbSe)	0.3 eV
Mercury Cadmium Telluride ($Hg_{1-x}Cd_xTe$)	
x=0	-0.142 eV
x=1	1.49 eV

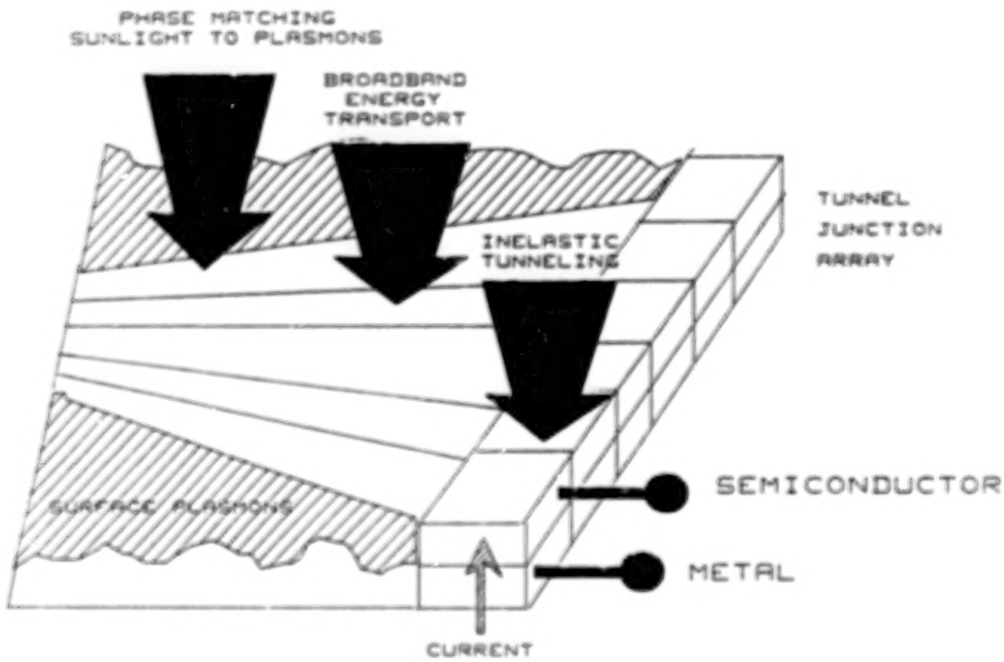
PLASMON-ASSISTED INELASTIC ELECTRON TUNNELING

PHOTON $\rightsquigarrow$ (JUNCTION) PLASMON →

→ ENERGETIC e^- →

→ TUNNELING ACROSS A BARRIER

EXTRACTING POWER FROM
SURFACE PLASMA OSCILLATIONS



from -
L. Anderson (NASA)

COMMENTS ON DESIGN

MAXIMIZE COUPLING OF EM WAVES TO SPO

(I) THIN METAL FILM
(II) HIGH PLASMA OSCILLATION FREQUENCY
(III) LOW RESISTIVITY METAL
(IV) LOW REFLECTIVITY METAL

MAXIMIZE TUNNELING CURRENT

(I) HIGH DOPING CONCENTRATION
(II) LOW EFFECTIVE BARRIER
(III) LOW TEMPERATURE OPERATION

MAXIMIZE RESPONSE TIME

(I) LOW RESISTANCE & CAPACITANCE
(II) HIGH ELECTRON MOBILITY

(I) TUNGSTEN SILICIDE THICKNESS OF 200 TO 300 ANGSTROMS.

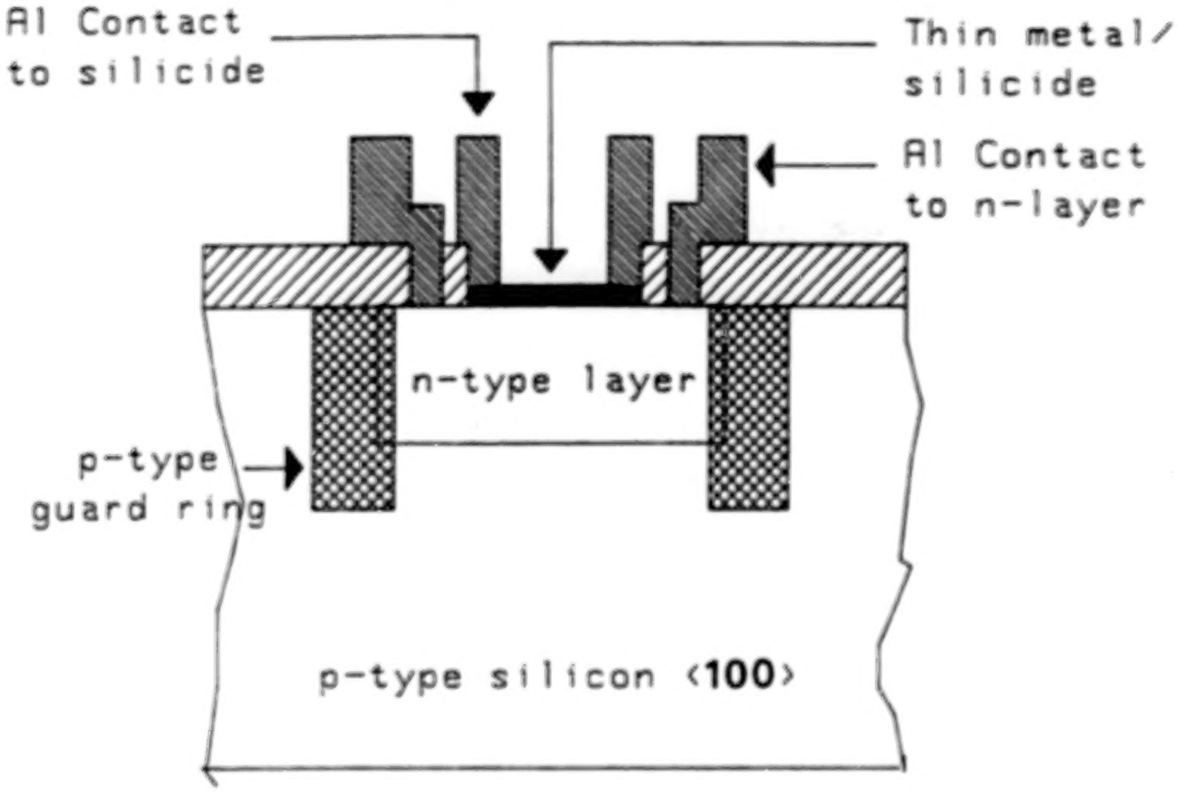
(II) CONTACT METAL (AL) THICKNESS OF 1 uM.

(III) THE DIFFUSED N-TYPE LAYER FORMING THE ACTIVE DEVICE WAS 1 uM DEEP.

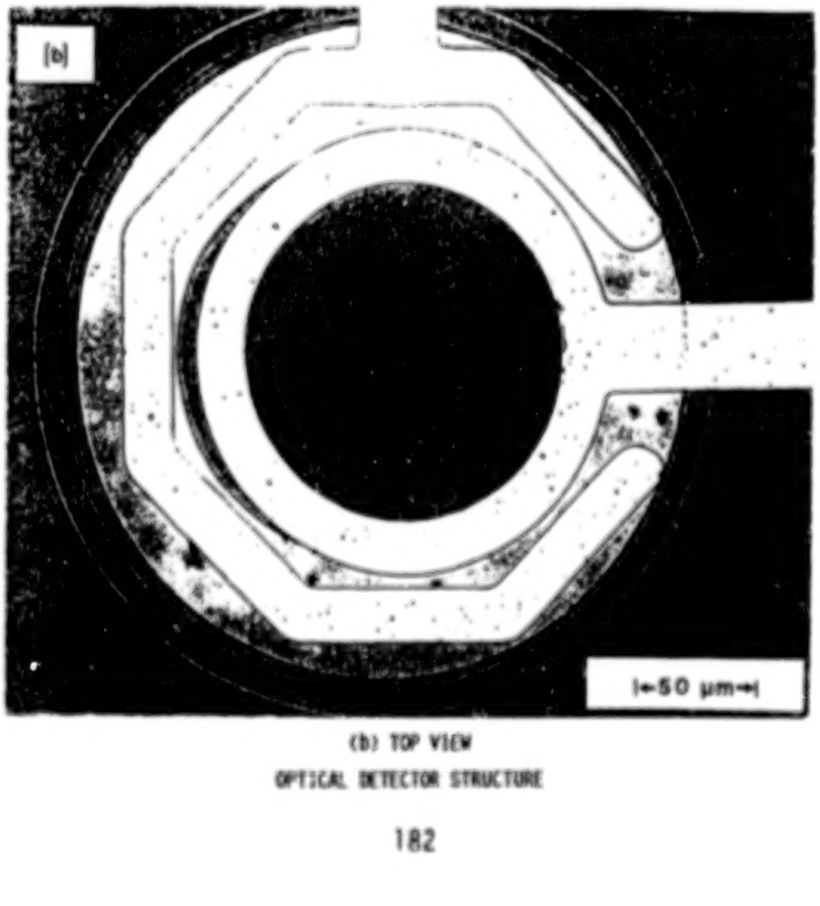
(IV) THE P-TYPE GUARD RING FOR THE GUARD RING SCHOTTKY DIODE WAS 1.5 uM DEEP.

(V) THE DOPING CONCENTRATION OF THE N-TYPE LAYER WAS CLOSED TO THE SOLID SOLUBILITY LIMIT FOR PHOSPHOROUS IN SILICON 1×10^{20} cm^{-3}.

(VI) THE SUBSTRATE WAS HIGH RESISTIVITY P-TYPE <100> SILICON.



(a) CROSS SECTION



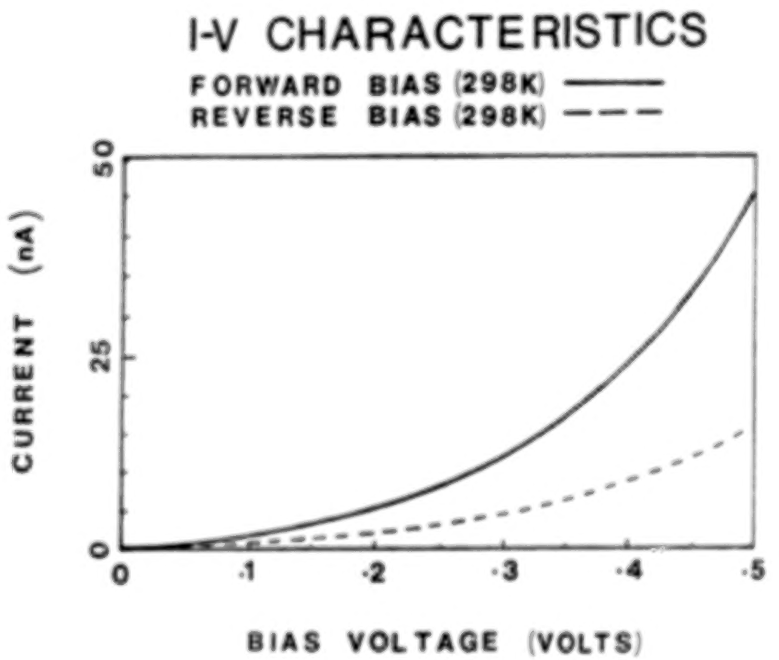
(b) TOP VIEW

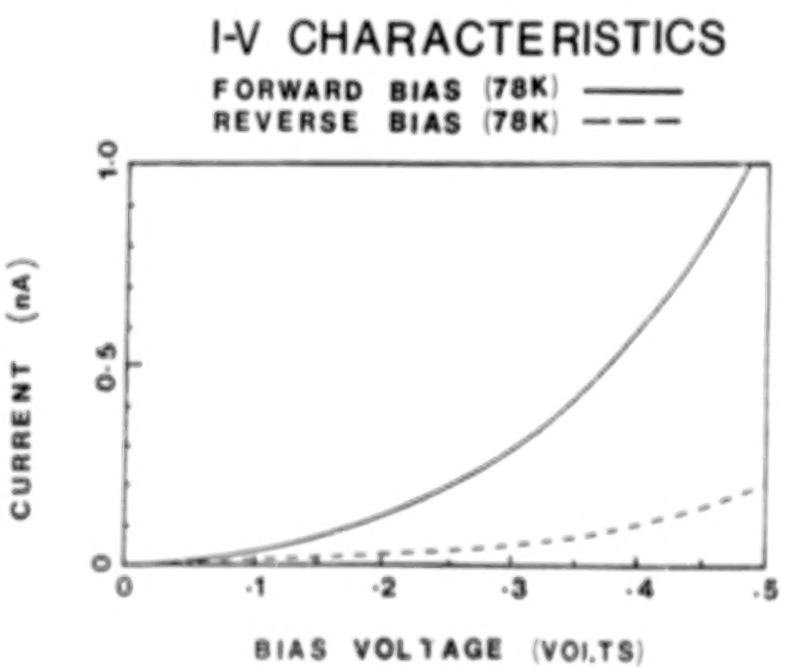
OPTICAL DETECTOR STRUCTURE

DEVICE CHARACTERIZATION

- I - V MEASUREMENTS
- C - V MEASUREMENTS
- SHEET RESISTANCE MEASUREMENTS
- INCLUDING RTA OF WSi_2

- OPTICAL RESPONSE
  - VISIBLE
  - FAR-INFRARED





- UTILITY OF THE SILICIDE AS A GATE AND INTERCONNECT MATERIAL FOR VLSI
    - GOOD ADHESION PROPERTIES
    - HIGH TEMPERATURE STABILITY
    - LOW RESISTIVITY
    - SUITABLE FOR GROWING AN INSULATING LAYER BY OXIDATION

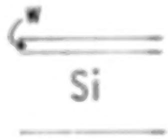
SAMPLE PREPARATION

DEPOSITION OF TUNGSTEN

Magnetron Sputtered at a base pressure of 10^{-7} Torr.

Film Thickness 20 nm.

Uniformity 1 nm.



FORMATION OF TUNGSTEN SILICIDE

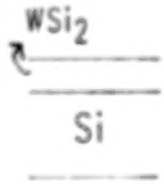
Rapid Thermal Annealing in $10\%\ H_2$ and 90% Ar Atmosphere

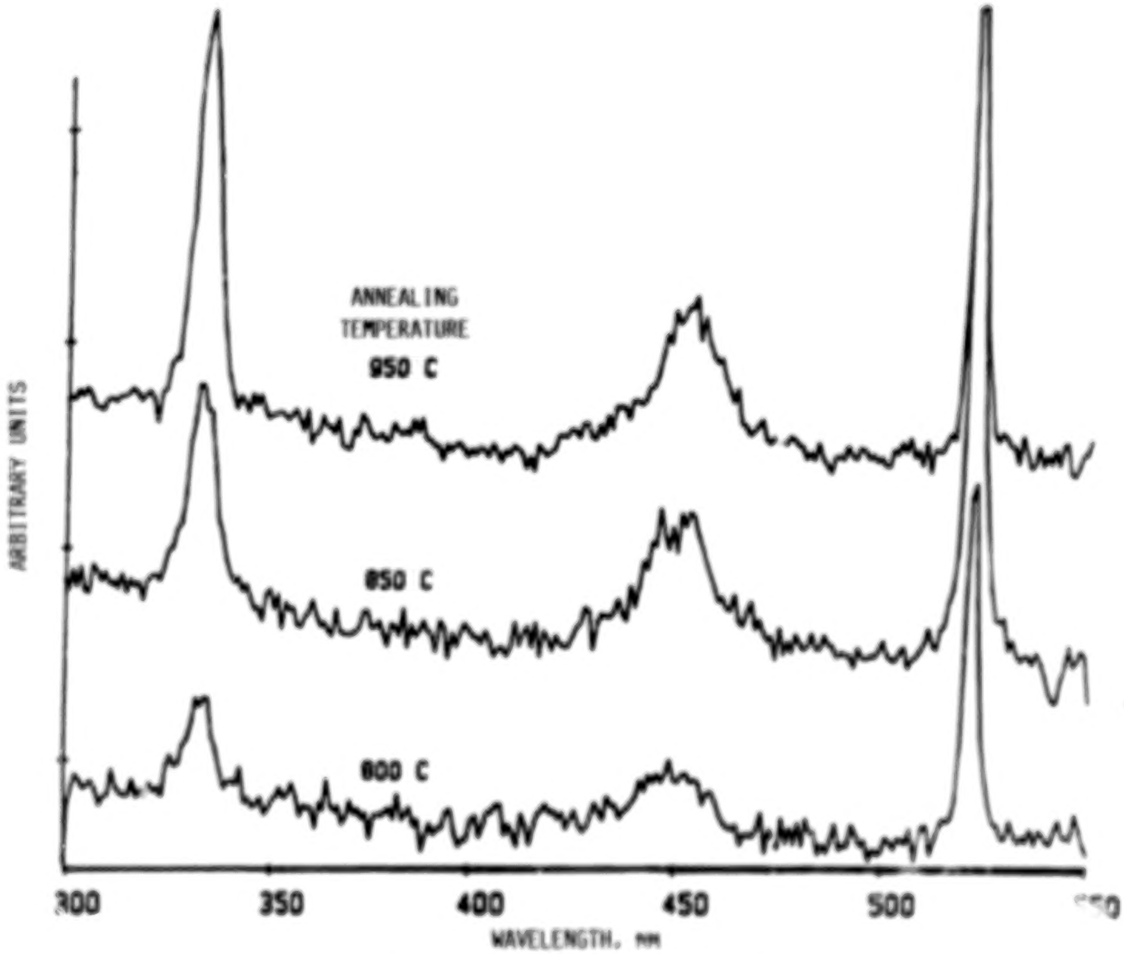
Time 90s/20s

Thickness 50 nm.

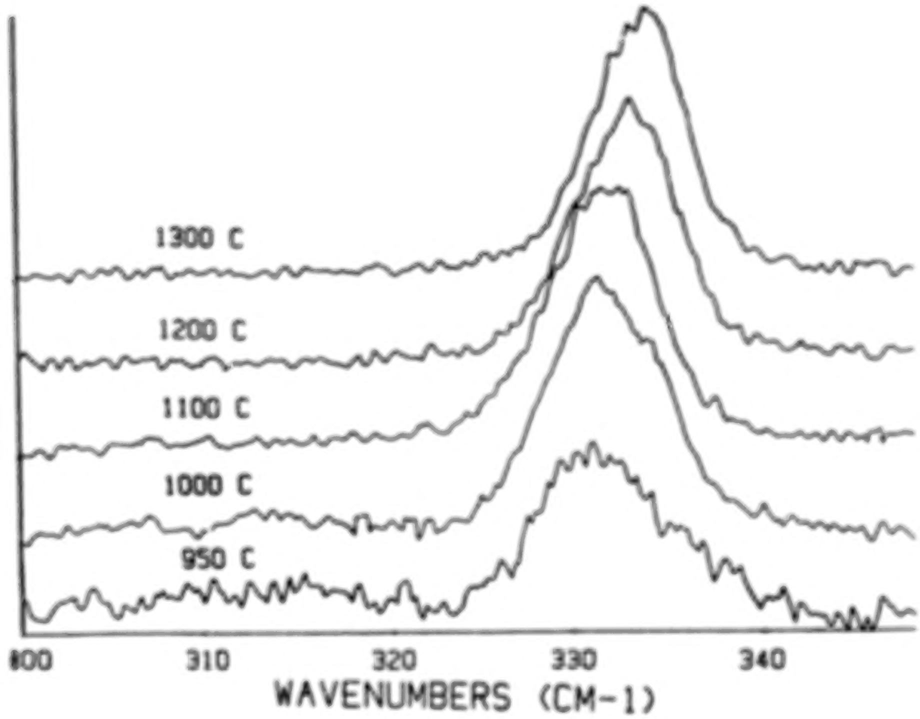
Stoichiometry $WSi_{1.4}$ (RBS)

Temperature 800C -





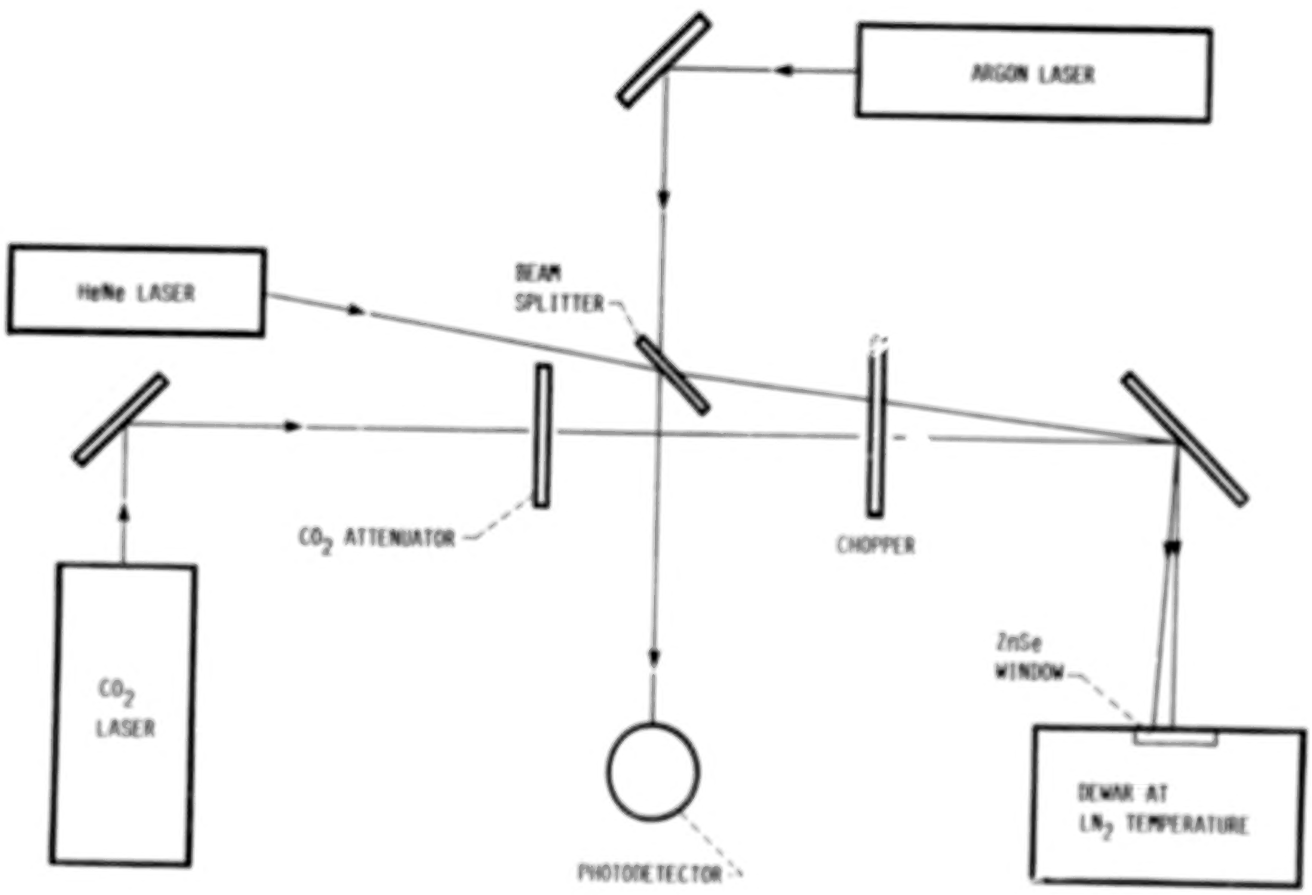
RESPONSIVITY OF TUNGSTEN DIODE



Raman spectra of rapid thermal annealed tungsten silicide

Properties of tungsten silicide films rapid thermally annealed at different temperatures

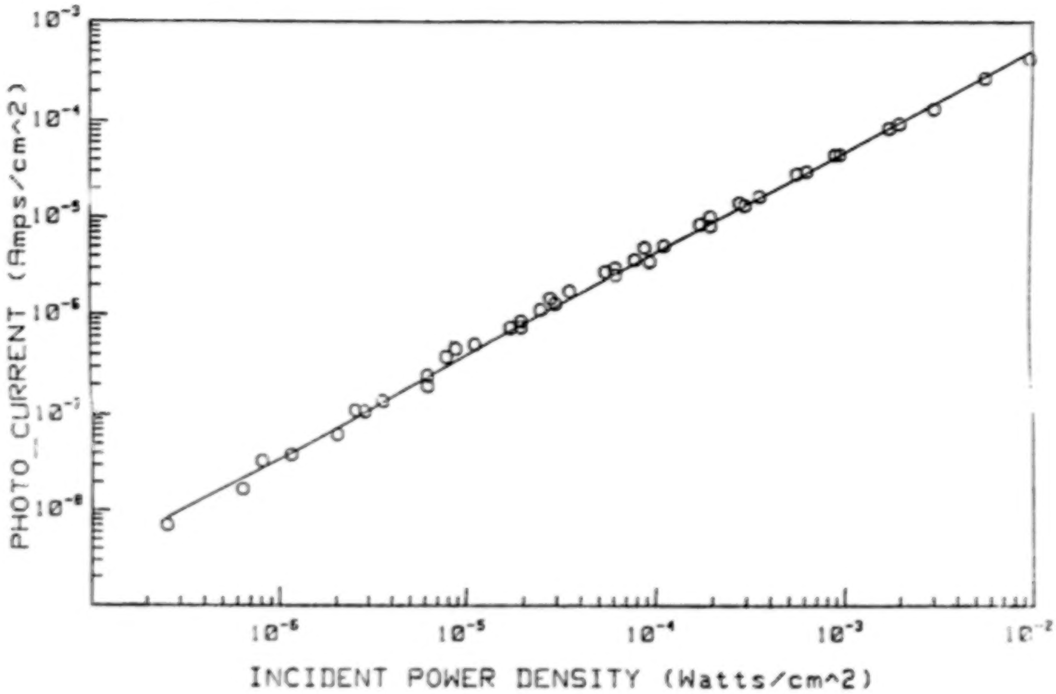
Material	RTA temp C	Sheet Resistance	Intensity of 332cm−1 Raman line	Peak Position of 332cm−1 line	FWHM (cm−1)	Ratio of Area under 332cm−1 Peak
W	---	68.34	---	---	---	---
WSi2	950	30.9	31.7	331.0	8.7	1.0
WSi2	1000	24.5	86.6	332.0	7.6	1.19
WSi2	1100	20.7	93.3	334.1	6.4	1.31
WSi2	1200	24.2	105.7	333.7	6.1	1.21
WSi2	1300	314.6	128.6	334.0	5.9	1.25



SETUP FOR DIODE TESTING

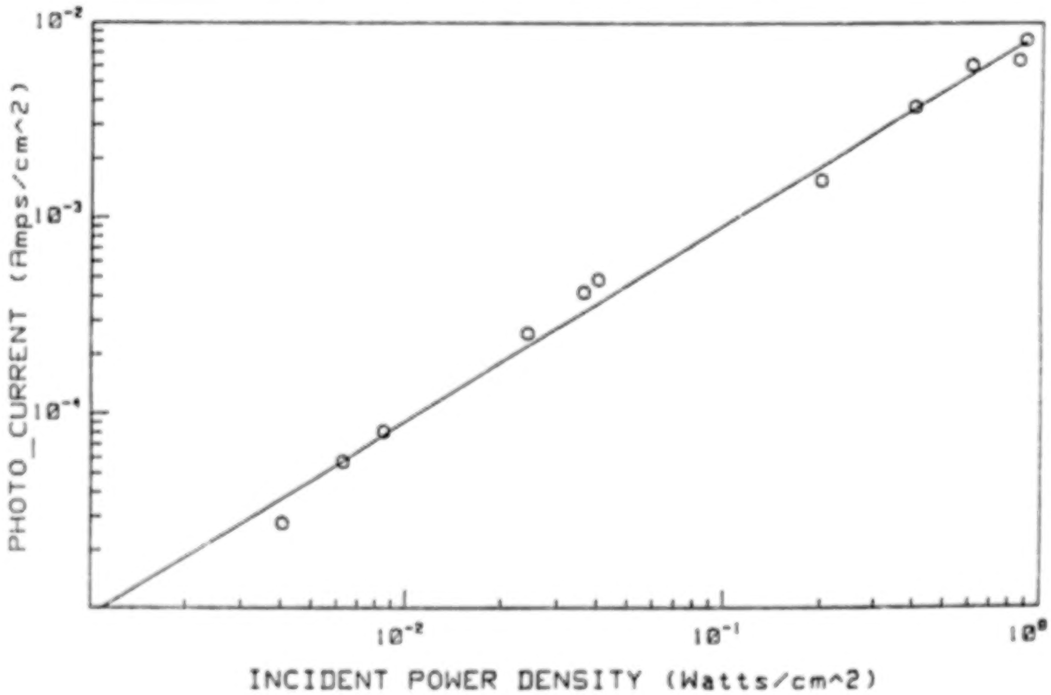
RESPONSE TO HeNe LASER (6328 Å)

Measurement Temperature 78 °K

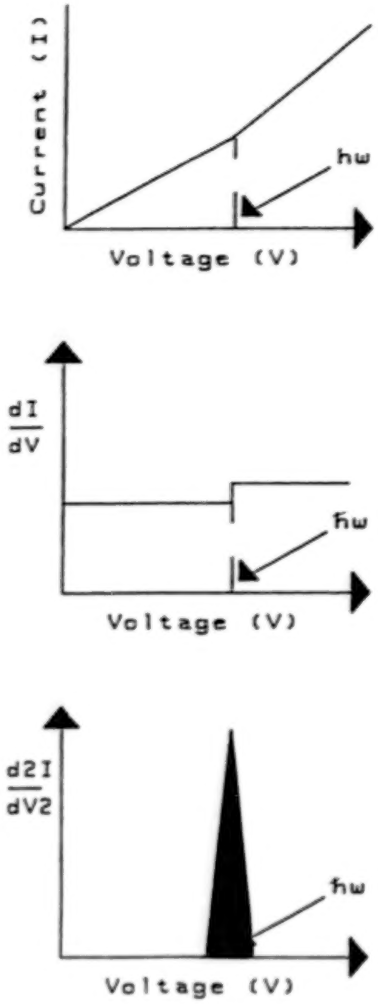


RESPONSE TO ARGON LASER (5145 Å)

Measurement Temperature 78 °K

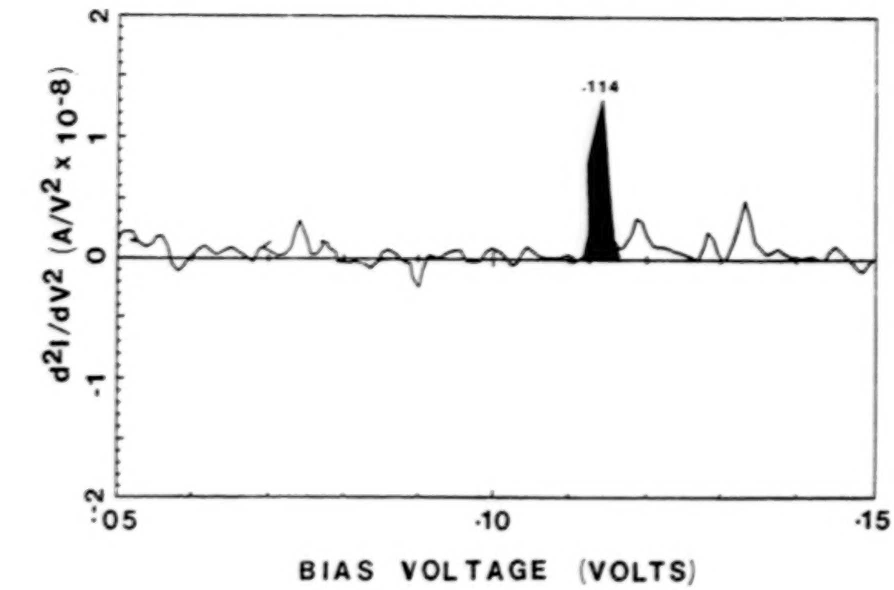


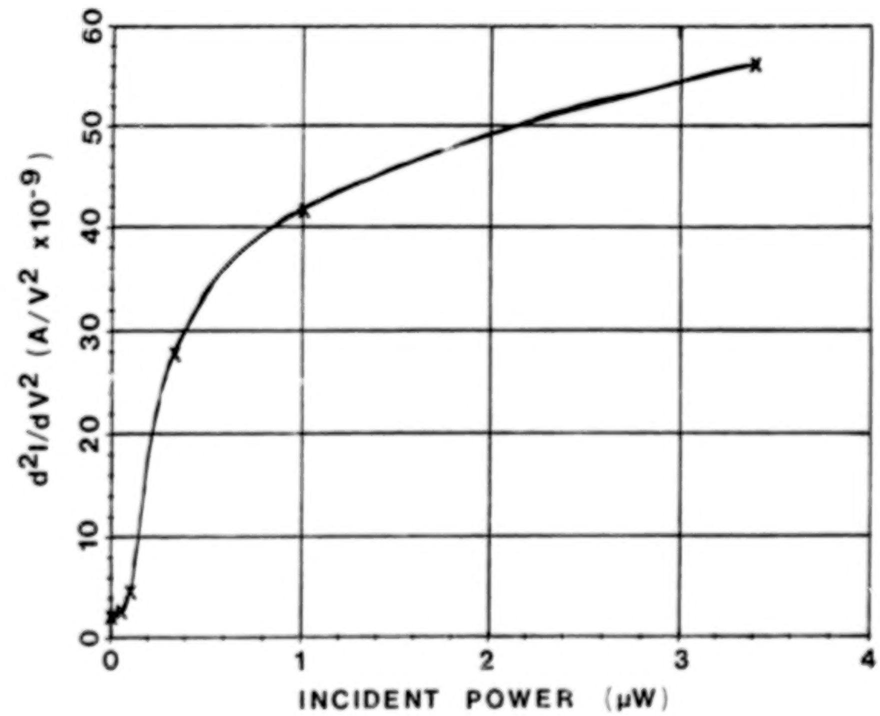
C-3



THEORETICAL RESPONSIVITY CURVES

Second Harmonic Response





SUMMARY

* Designed and fabricated a tungsten silicide Schottky barrier diode
* A RTA silicide process was investigated
* Electrical characterization was carried out
* * Demonstrated response to optical radiation at a wavelength of 10.6 microns
* Future directions identified.

FUTURE EFFORTS

* Optical Response of present Small Structures
* Fabrication and Characterization of Sub-Micron Structures
* Develop electrode/antenna structures
* Optical response and quantum efficiency of arrays of sub-micron structures.

CONCLUSIONS

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Cleveland, Ohio 44135

The free-space power transmission concept has been demonstrated. Several prototype systems and components have been developed and successfully tested at 2.45 GHz. Extensive studies have determined the applicability of this concept to missions such as the SPS, the Canadian SHARP, and the CO-OPS Program.

The applicability or practicality of this concept could only be determined by its competitiveness over more conventional techniques of power generation in space (solar and nuclear). In most NASA and DOD scenarios, the separation distance between the transmitter and receiver ranges from a few tens to several thousand kilometers. Because of mass constraints, antenna sizes should be kept to a minimum, forcing the system to operate at higher frequencies and, consequently, to attain a high-power interception efficiency. To remain competitive, this kind of system should operate at frequencies above 100 GHz.

No system above 2.45 GHz has been developed. A prototype system operating at 35 GHz seems to be the next logical step, since technology is already available at that frequency. Technology at 100 GHz and above seem to be feasible, but not available in the immediate future. Development of antenna, RF-power-generation, and rectenna technology is necessary for working systems at these frequencies.

A substantial effort in these areas is being sponsored by the Government, the military, academia, and industry. Although this effort is not directed toward the development of a free-space power transmission system, the outcome of these programs is applicable to beam power technology. A combined effort of all the parties involved should contribute to an early and cost-effective development of such technology.

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15. Supplementary Notes

16. Abstract

NASA Lewis Research Center organized a workshop on technology availability for free-space power transmission (beam power). This document contains a collection of viewgraph presentations that describes the effort by academia, industry and our national laboratories in the area of high-frequency, high-power technology applicable to free-space power transmission systems. The areas covered were rectenna technology, high-frequency, high-power generation (gyrotrons, solar pumped lasers, and free electron lasers), and antenna technology. This workshop took place on March 29-30, 1988, at NASA Lewis Research Center.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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